LITHIUM-ION BATTERIES PERFORMANCE OPTIMIZATION FOR VEHICLE-TO-GRID (V2G) INTEGRATION IN THE SMART GRID

BY

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LIST OF SYMBOLS

Symbol	Definition
OECD	Organization for Economic Co-operation and Development
HDI	Human Development Index
GDP	Gross Domestic Product
IEA	International Energy Agency
η	Generation Efficiency
PCA	Process Chain Analysis
LCA	Life Cycle Assessment
EROI	Energy Returned on Energy Invested
N	Net Energy
P	Production
S_1	Conversion energy input
S_2	Embodied energy in the system
ER	Energy Returned
EI	Energy Invested
GHG	Green House Gasses
RE	Renewable Energy
AC	Alternate Current
EV	Electric Vehicle
BEV	Battery Electric Vehicle
FCEV	Hydrogen Cell Fuel Electric Vehicle
ICEV	Internal Combustion Electric Vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Electric Vehicle
NiMH	Nickel Metal-Hybrid
LIB	Lithium-Ion Battery
NASA	National Aeronautics and Space Administration

CE	Consumer Electronics
CEMAC	Clean Energy Manufacturing Analysis Centre
DOE	Department of Energy
R&D	Research and Development
IC	Internal Combustion
ESOI	Energy Stored on Energy Invested
PHS	Pumped Hydroelectric Storage
CAES	Compressed Air Energy Storage
V2G	Vehicle to Grid
G2V	Grid to Vehicle
N_c	Number of cycles
DOD	Depth Of Discharge
DOD_i	Depth Of Discharge initial
DOD_f	Depth Of Discharge final
SOC	State Of Charge
SOC_i	State Of Charge initial
SOC_f	State Of Charge final
E_B	Capacity
δ	Percentage of the battery used
E_c	Energy consumed
d	Distance
R	Range

ABSTRACT

Energy management is a series of systematic procedures used to realize economics of energy efficiency potentials (Bertoldi & Atanasiu, 2007). Design of energy efficiency strategies in industry in general aims at both gaining knowledge and developing strategies that can assist industry with achieving energy efficiency targets. Significant energy-efficiency improvement opportunities already exist in industrial sectors, many of which are cost-effective (Eichhammer & Wilhelm, 1997). Energy efficiency is specifically important in the battery industry which is becoming a sector with significant impact on the global economy: (a) has potentials to provide access to renewable energy sources (in vehicle to grid systems), (b) provides energy security (by storing excess wind and solar energy for future use), and (c) reduces GHG emissions by promoting use of renewable energy (Rao and Rao, 2011).

This study demonstrates the importance of undertaking energy efficiency measures in battery industry focusing on the application of the EROI (energy returned to society on the invested in making batteries), and ESOI (energy stored over the life of battery on invested in making batteries). The theoretical analysis in this study indicated that in addition to estimating ESOI as a measure of battery efficiency, industry needs to also consider EROI as a method for assessing sustainability of the batteries, particularly when those are considered as a distributed source of renewable in EVs (Electric Vehicles) with smart grid configuration (V2G systems). Modeling results also indicated that efficiency

of the batteries in the EVs with V2G configuration could be maximized if the daily depth of batteries discharge (DOD) is balanced against their expected lifespans.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Automation, the increase in houses' commodities and the growth of developing countries (economic and in population) are the mainly reasons of the significant increase in the world's energy consumption which is not forecast to decrease (Fawkes, Oung & Thorpe, 2016). Since the global energy production is lead by fossil resources, the world is experiencing an unstoppable increase in pollution, in the CO_2 emitted. If we keep consuming at this rate, by 2040 the concentration of GHG will be such that nature will start releasing natural CO_2 reaching a state of non-return. This raise in CO_2 emissions causes the increase in world's temperature, according to the green house effect, leading into the well-known climate change that will affect the natural environment by raising sea levels causing floods, extreme weather and shifting rainfalls affecting our food supply and risking wildlife. To sum up, if the world's energy generation keeps this path, the Earth and the human kind will be threaten to extinction (Hardy, 2003).

Part of the solution for reducing CO_2 emissions remains in generating electricity from renewable resources. However, the main drawback of these sources of energy is that the generation of energy is unpredictable. They cannot assure a steady supply of energy that can meet the electrical demand, consequently, utilities have to install extra capacity just to meet occasional demand peaks implying a significant waste of energy the major part of the time (Kobos, Erickson & Drennen, 2006).

In order to make this waste of energy available to the electric market through batteries, specifically, through lithium-ion batteries (LIB) which have been proven to have the best technology for storing energy up to 2017. Two different methods can be differentiated in order to store renewable energy through LIB. On the one hand, the super large batteries for grid storage which can store huge amounts of energy from the grid and on the other hand, smaller batteries adapted for Electric Vehicles (EV) that act as a dispersed storage system (Dunn, Kamath & Tarascon, 2011).

Aside from generating energy from renewable resources, the rest of the solution for preventing global warming is linked to reducing energy waste by performing processes in a more efficient way (Murphy & Hall, 2010).

The method used in this project to calculate the efficiency of batteries has been providing the EROI (Energy returned on Energy Invested) and the ESOI (Energy Storage on Energy Returned) values showing that the most efficient way of storing energy is using lithium-ion batteries in EVs as a distributed source of energy. This means not only to consider batteries as a way of storage but as a source of energy through the Vehicle to Grid (V2G) technique that allows vehicles to inject the remaining energy stored in the battery to the grid. However, different factors have to be taken into account in order to optimize that efficiency such as selecting the appropriate battery according to the distance traveled and injecting the exact energy to the grid in order to balance the battery life and the amount of energy that it can deliver over its life.

1.2 Project goals and objectives

The main goal and objectives of this project is to contribute to the literature in the area of management of energy technology in support of sustainable development. To meet this goal, we investigated application of the electric batteries as a sustainable energy system in management of the electric Grid systems. More specifically it has been aimed at:

I. Understanding application of the lithium-ion batteries for electric vehicles with vehicle to grid configuration. Describing conditions under which batteries can perform as both storage and a source of energy, while also evaluating social, economic and environmental impacts of using batteries as a distributed source of energy in the electric grid system.

II. Supporting sustainable industrial technology management by demonstrating application of strategic tools for analyzing energy efficiency in battery manufacturing in order to address inefficiencies in both use of energy and/or selection of energy sources for manufacturing batteries focusing on both operation/supply chain and product design.

III. Studying the impact and consequences of the solutions provided in real cases through data gathered from electric vehicles available in the market that use lithium-ion batteries with a vehicle to grid configuration.

IV. Providing suggestions for improvements and the optimization of energy use in industry according to sustainable economic development/manufacturing criteria (i.e. estimating impact of improvement options and alternatives on economic, environmental, and social systems).

1.3 Chapter’s summary

Chapter 2 describes the current global energy situation, particularly in regard to demand and development. The chapter also introduces the consequences of that situation and the future perspectives as well as possible solutions for facing them. One of these solutions is energy efficiency for improving the industrial energy usage, particularly in developing countries, in this case, applied to battery storage industry. Therefore, the chapter also focuses on the explanation of the EROI value (Energy Returned on Energy Invested) as a way for calculating the efficiency of systems.

Chapter 3 discusses energy use and efficiency strategies in battery. There is a discussion in the evaluation of the energy invested in the supply chain and manufacturing of the batteries. This industry was selected due to the vital role batteries could play in successful utilization of the renewable energy systems (also as efficient use of non-renewable carbon-based energy). This chapter is devoted to providing an analysis of the battery technology/industry and estimation of the energy use/invested in in manufacturing of the batteries. Information provided in this chapter is then utilized in chapter 4 when analyzing the application of the batteries as distributed sources of the renewable energy in Smart Grids.

Chapter 4 introduces the operation and supply chain of lithium ion battery industry, energy use, its advantages and disadvantages, the challenges of this technology, the market situation and the future perspectives. There is also and overview of the structural components and the principle of operations of the battery as well as its supply chain and manufacturing processes.

Chapter 5 introduces the concept of efficiency regarding lithium ion batteries; the chapter describes and differentiates EROI and ESOI values, focusing on batteries as energy source linked to the vehicle to grid technique. Then it is calculated the EROI value of lithium-ion batteries for different cases in order to provide conclusions about how to increase its efficiency and make these type of batteries more sustainable.

Chapter 6 shows the different strategies that can be applied for optimizing the EROI value of lithium-ion batteries for electric vehicles with a vehicle to grid configuration through both increasing the energy returned and decreasing the energy invested. The chapter also discusses the impact of applying those strategies in both social and economic level.

Chapter 7 presents a summary of the project including the rationale and motivation, goals and objectives, methodological approach used for the analysis of the theoretical topics, results and conclusion The chapter concludes with a section listing future work and the next steps that should be taken in order to continue and expand the project.

CHAPTER 2

ENERGY DEMAND, EFFICIENCY AND STORAGE FOR SUSTAINABLE DEVELOPMENT

Chapter 2 describes the current global energy situation, particularly in regard to demand and development. The chapter also introduces the consequences of that situation and the future perspectives as well as possible solutions for facing them. One of these solutions is energy efficiency for improving the industrial energy usage, particularly in developing countries, in this case, applied to battery storage industry. Therefore, the chapter also focuses on the explanation of the EROI value (Energy Returned on Energy Invested) as a way for calculating the efficiency of systems.

2.1 Energy demand and development

According to Fawkes, Oung & Thorpe (2016), p. 11, as economies industrialize, grow and become dependent on more sophisticated infrastructure and technological systems, energy becomes even more important to individuals, enterprises and nations. The world's energy consumption is experiencing a significant increase, which it is not forecast to decrease due to the increase in automation, the increase in houses' amenities and the growth of developing countries among other reasons.

Figure 2-1 shows the annual evolution of the energy consumption per region. Global primary energy use in 1973 was 4,672 million tons of oil equivalent (mtoe). By 2015 this had increased to 13,541 mtoe. The graph allows us also to see the significant raise in consumption of the developing countries such as China, India and the non-OECD Americas that will mark a significant change in the global energetic scenario in the upcoming years (Fawkes, Oung & Thorpe, 2016, p. 9).

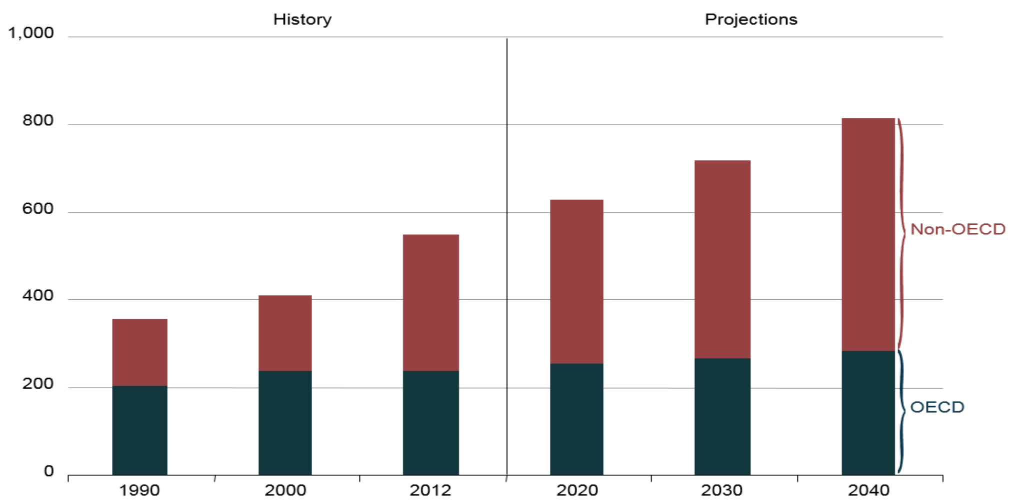


Figure 2-1. Historical and projected annual energy demand by region (quadrillion Btu)
Source: U.S. Energy Information Administration (www.eia.gov/outlooks/ieo/world.php)

Referring to Hall & Klitgaard (2011) work, we are submerged in a cycle in which the technological breakthroughs result into the increase of the welfare that implies greater energy consumption. Therefore, the increase in energy consumption is directly correlated to the standards of living or the Human Development Index (HDI). The HDI is a composite statistic of life expectancy, per capita income and education indicators, which are used to rank countries into four tiers of human development. This index goes further in calculating the standards of living compared to the Gross Domestic Product (GDP), which only measures the wealth of a country but not necessarily the human well being itself.

Figure 2-2 depicts the correlation between the HDI and the per capita Primary Power Consumption indicating that the more developed the country is, the more energy is consumed. In that context, it has to be mentioned the raising in this graph of India and China as developing countries during the last years. However, the main objective in efficiency should be to follow the example of Germany which even though having a high HDI, they manage to have a low per capita power consumption (Geller, Harrington, Rosenfeld, Tanishima, & Unander, 2006).

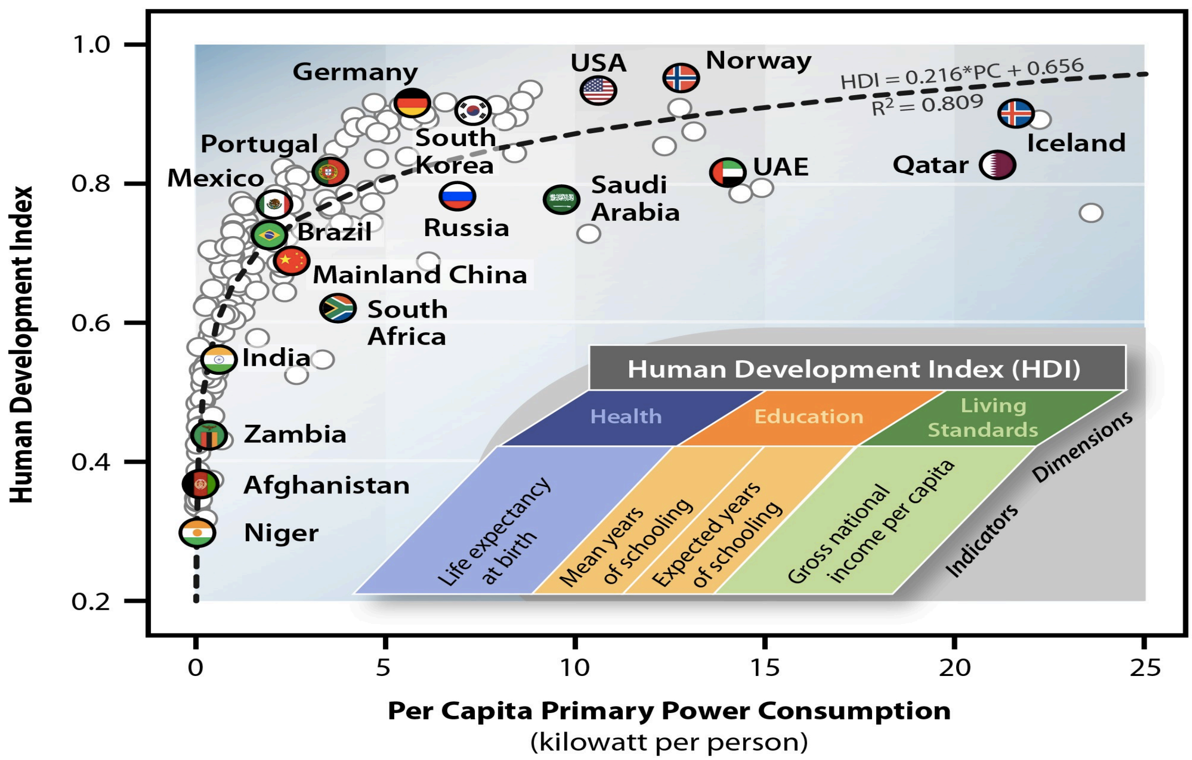


Figure 2-2. Human Development Index by country versus per capita power consumption
Source: Michigan State University, Dept. of Chemical Engineering
(www.ourenergypolicy.org/growing-poor-slowly-why-we-must-have-renewable-energy/)

Not only the increase of world's economies and development of countries but also the raise in world's population is affecting the demand of energy. The increase in population is a really dramatic issue to take into account result of the development of technology that has lead into the reduction of birth deaths and the extension of life expectancy (Chontanawat, Hunt & Pierse, 2008).

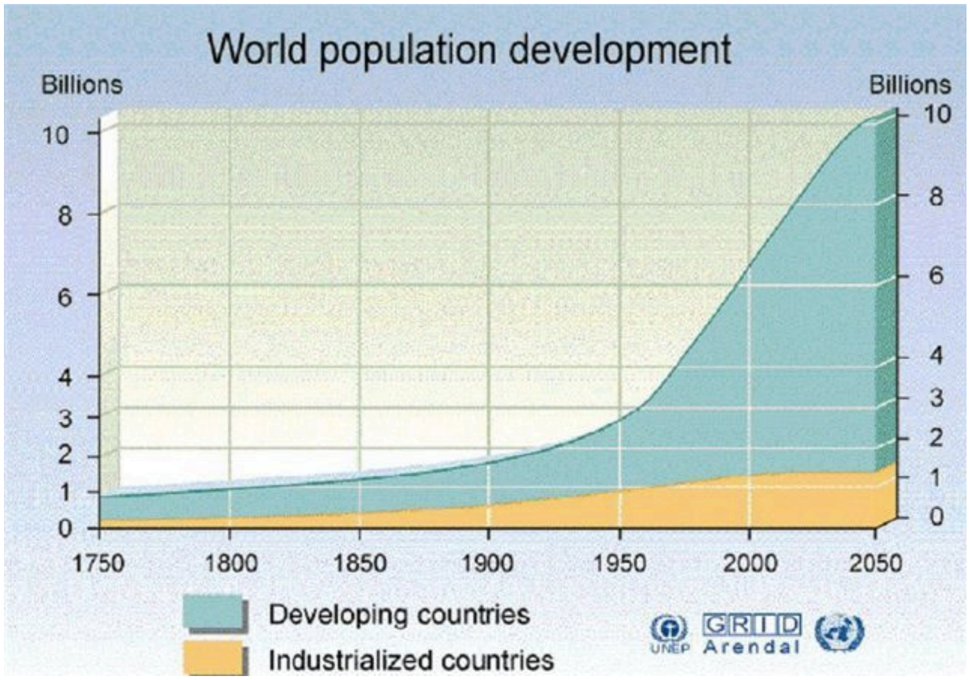


Figure 2-3. World's population per country according to its level of development
Source: United Nations World's population prospects
(www.pennspectrum.org/2013/12/01/what-is-the-implication-of-a-growing-world-population/)

According to Figure 2-3, this growth in world's population has been highly remarked the last century primarily by developing countries such as China and Africa's countries. Nowadays, there is a population of 7 billion people, if we continue growing at this same rate, considering that this growth is exponential, by 2050 the world's population will be over 10 billion people. The main issue of this growth will be scarcity, we are immersed in an unsustainable system according that food, water, metals, fossil fuels resources will run out one day. If birth rate does not fall as it should, the population will continue to rise. It will rise up to a point that will exceed the carrying capacity of the Earth and people will start to starve so that the population will start falling. In 2050 will start the Dark Age, by 2061 50% of population will wipe out and by 2071 a 75% of the population will wipe out. (Armaroli & Balzani, 2007).

Referring to Hansen et al. (2006) work, even though there are several plans for reducing fossil fuels dependency, by the year 2035, the energy consumption will have increased up to 49% according to population growth, and we still will be dependent on fossil fuels. It seems that not only our world is deteriorating faster than expected due to climate change, but also that we are overestimating the amount of greenhouse gases to cause irreversible damage. As Solomon, Plattner, Knutti, & Friedlingstein (2009) investigated, at 2017 we are at a concentration of 402 ppm, having reached an increase of 1ºC in the planet's temperature respect year 1961. With this increase in temperature, we are able to see some effects such as the sea ice melts and the disappearance of glaciers.

The real problem though, will be at the point we will reach 450 ppm, with a 2ºC increase in the world's temperature. In that point and with that level of CO_2 concentration, a loop will be formed where natural greenhouse gases in the planet will be released increasing the temperature of the Earth more and more.

Therefore, once we reach that point, it won't matter stop emitting CO_2 as it will be naturally released due to the temperature we will have reached. Once having reach that point, the Amazon will dry up, the Permafrost will melt, entire regions will experience crop failures, starvation will increase, the west Antarctic ice melt will be irreversible (5m sea rise), the sea level rise will threaten New York, Tokyo, Shanghai, London…

Figure 2-4 represents the evolution of the global temperature caused by the increase in CO_2 emissions, where it can be seen that it is constantly increasing.

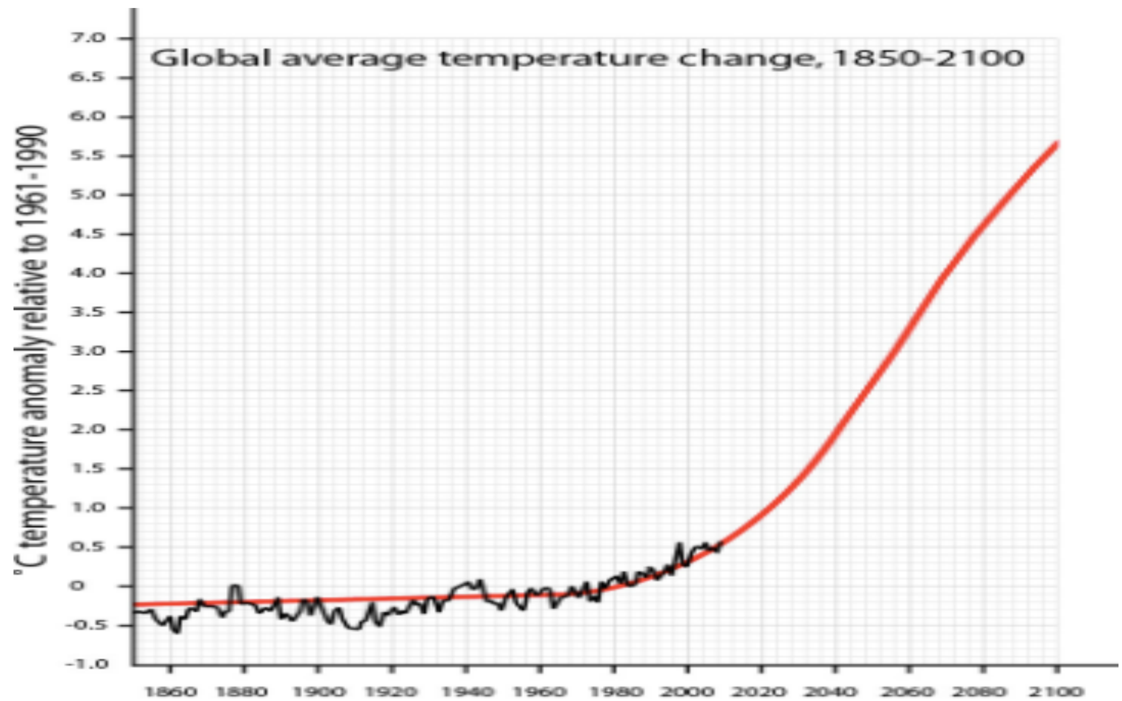


Figure 2-4. Projected evolution of the global temperature (1860-2100)
Source: Energy and the environment (http://www.futuretimeline.net/resources/energy-environment.htm#.WUg_cRPytAY)

Several solutions have been proposed in order to avoid the catastrophe such as migrating to Mars, that the develop countries severely reduce their energy consumption and resources and distribute them to underdeveloped countries or policies for stopping the growth of population. However, those solutions are not likely to happen at least in a near future. The solution starts by decreasing the use of fossil fuels by installing renewable energy and the use of technology for developing new ways of doing things in order to reduce energy consumption and demand, be more efficient.

Figure 2-5 depicts the high dependency of our energy system in fossil fuels. It can be seen that despite the decrease in the rate of growth of petroleum consumption (but still dependent on it) due to extinction of the resource that increases prices, coal is taking the lead as energy producer, a pollutant material that generates a huge amount of CO_2 when burned. Renewables have still a long way to overcome fossil fuels dependency. What is more, the reality is that we will never be able to achieve the goal of powering our current lifestyle on renewable energy, we will run out of materials before building smart grids and enough renewable for the world (Boyle, 1997).

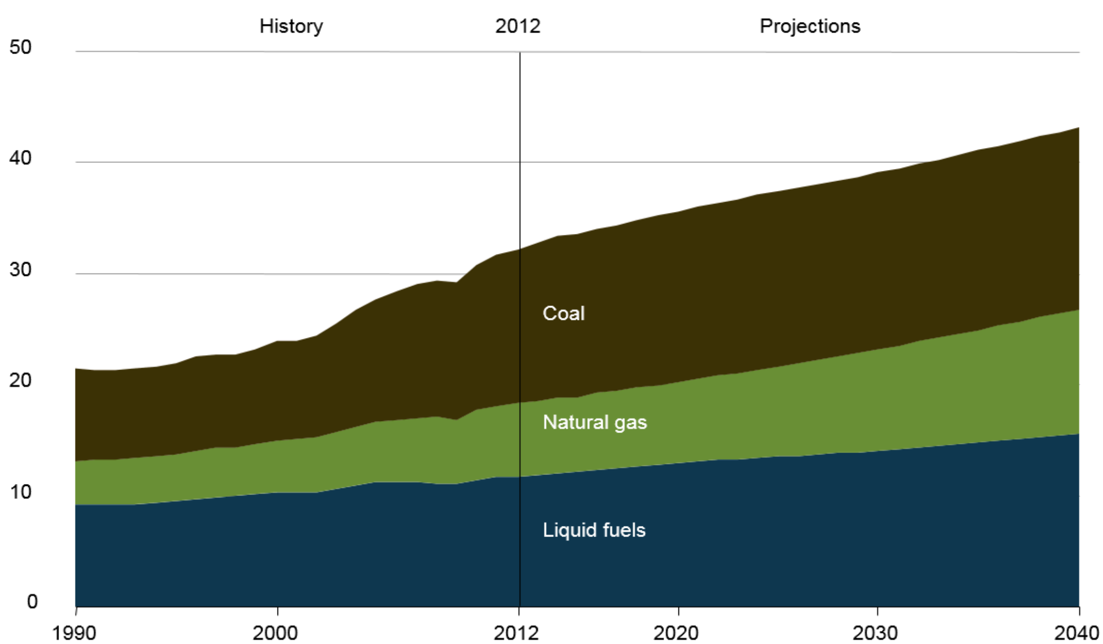


Figure 2-5. Global carbon emission according to the type of fossil fuel resource
Source: U.S. Energy Information Administration
(www.eia.gov/outlooks/ieo/exec_summ.php)

The future solution to the world's issues then has to meet sustainability needs in order not to make the same mistake. Therefore, the solution has to balance social progress, environmental stewardship and economic growth at the time it has to deal with depleting energy resources, exponential population growth, environmental and climate change and economics and sustainability (Peter, 2003).

This project considers that the solution is not unique and that is the combination of several actions. One of the solutions that seeks sustainability and has a significant impact in the world's economy, society and environment is the energy efficiency management which will be discussed in section 2.2. An overview of the importance of the renewable energy sources and energy storage to sustainable development is provided in section 2.3.

2.2 Renewable energy systems and energy efficiency in battery industry

This section addresses inefficiencies in both use of energy and/or selection of energy sources in industrial operations using supply chain mapping and diagnostic models, tools, and techniques. Suggestions for the improvements and optimization of energy use in industry are provided according to sustainable economic development/manufacturing criteria (i.e. estimating impact of improvement options and alternatives on economic, environmental, and social systems). Applications of those strategies are then discussed in a case study that focuses on battery industry. We discuss that applicability of the energy-efficiency options including cross-cutting and sector-specific measures, are contingent to careful considerations of the operation and supply chain systems of the industry. The main goal and objective of this research is to design least cost energy efficiency models for battery industry focusing on both operation/supply chain and product design. Battery industry is selected because of its vital rule in supporting use of renewable energy systems.

2.2.1 Energy efficiency fundamental

According to Fawkes, Oung & Thorpe (2016), p. 15, interest in improving energy efficiency is increasing at corporate, local, national and international levels around the world. In the words of the G8 Clean Energy and Development Report; "Improving end-use efficiency offers the greatest opportunity to address energy security, price and environmental concerns". Energy efficiency is also increasingly being recognized as being profitable without subsidies and capable of delivering multiple other non-energy benefits. Amongst these are: better productivity, job creation, reduced fuel poverty and improved public health. These benefits have recently been recognized due to pioneering work by the International Energy Agency (IEA, 2014a).

Energy efficiency is a widely used term that can be classified in within 4 types according to its meaning:

- **Generation efficiency:** This is the electric power plant efficiency (η) and it is defined as the ratio between the useful electricity output from the generating unit and the energy value of the energy source supplied to the unit in the same period of time (Woodbank communications Ltd, 2005).
- **Conversion efficiency:** This is the efficiency with which the converter performs its function and it is usually expressed as a ratio of output magnitude

to an input magnitude. For example the conversion from chemical energy into electricity in a battery (Wiley, 2004).

- **Appliance efficiency:** This kind of efficiency indicates the ratio of input energy converted into useful work by an appliance (Web Finance Inc., 2017).
- **Economic efficiency:** This type of efficiency refers to the ratio of resources and energy used to produce goods and service. This type of efficiency always improves profitability and is a necessary part of the strategy for adapting to resource constraints in a prosperous manner. As it has been seen there is currently a direct coupling between the wealth of a country and its energy use (Web Finance Inc., 2017).

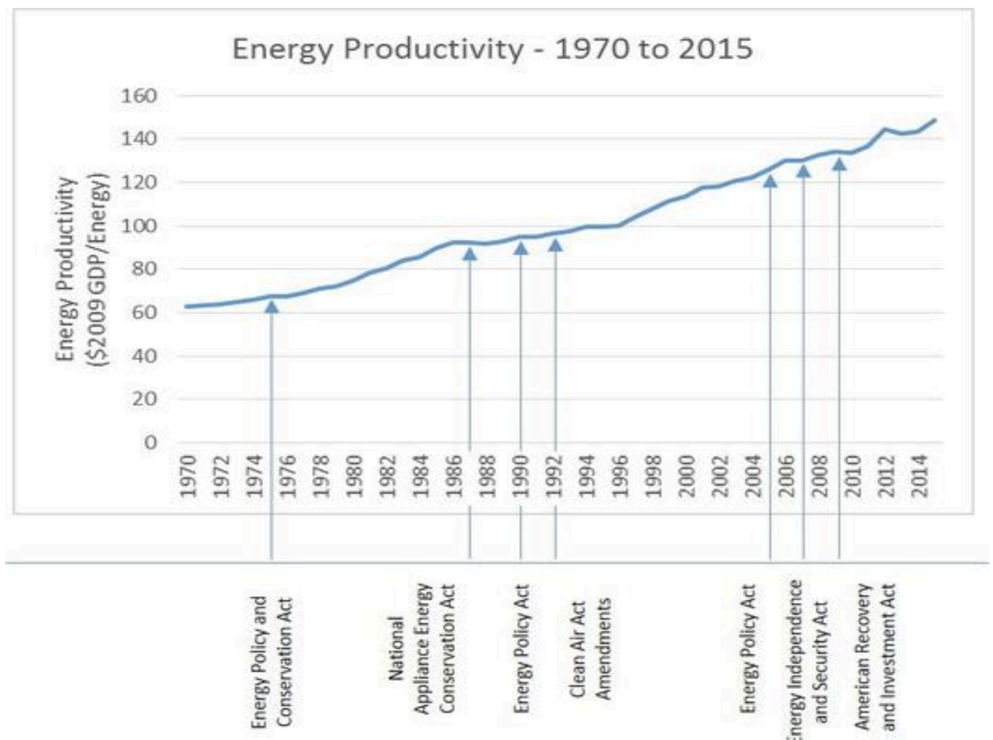


Figure 2-6. Energy productivity evolution from 1970 to 2015
Source: Alliance (https://www.ase.org/blog/earth-day-1970-present-what-long-productive-trip-its-been)

In that context it has to be mentioned the energy productivity ratio that measures economic output versus the energy input shown in Figure 2-6. The higher the ratio, the more efficiently energy is being used. Worldwide, between 2001 and 2011, it increased by an average of 1.3% per annum. Improving the rate of increase in energy productivity is necessary to achieve a low carbon future and addressing environmental constraints.

Without energy efficiency, analysis shows that global energy consumption in 2014 would have increased 2.1% rather than the actual rate of 0.7%. This suggests that energy efficiency saved 122 mtoe (IEA, 2015b). The IEA also estimates that investments in energy efficiency since 1990 saved a cumulative 520 mtoe (IEA, 2015a).

Another method of measuring the energy efficiency of a nation's economy is through energy intensity, which is the amount of energy needed to produce a unit of GDP. In this scenario, high energy intensities will indicate a high price of converting energy into GDP, whereas low energy intensities indicate a low cost when converting energy into GDP.

Table 2-1 shows the percentage shares of world population, GDP and commercial energy consumption as well as the energy intensity of some nations. According to the energy intensity, the most energy efficient nation is India with a low value of energy intensity, indicating that even though the population is high, the manage to consume a low amount of energy in relation to their GDP, unlike the US that has 4 times less population and consumes 5 times more energy than India according that they have a higher GDP but the relationship between energy consumed and GDP (energy intensity) is higher leading into a worse energy efficiency system (Tiwari, 2000).

Table 2-1. Commercial energy consumption for selected countries
Source: http://data.worldbank.org/indicator/EG.EGY.PRIM.PP.KD

Country	% of world population 2011	% of world GDP 2011	% of world energy consumption 2011	Energy intensity
United States	4.5	19	19	9.8
Japan	1.8	5.6	4.2	6.9
Germany	1.2	3.9	2.7	7.6
United Kingdom	0.9	2.8	1.7	6.5
China	19	14	20	9.6
India	17	5.6	4.4	4.4

When talking about industries though, other methods are used in order to measure energy efficiency. Process Chain Analysis (PCA) is a method to audit any system over different production steps. It takes into account all the inputs and outputs such as energy resources and waste, of every step which are represented in terms of energy. PCA is used for calculating the specific energy and material flows and costs in order to provide a conceptual understanding. PCA approach is used in several types of analysis such as life cycle assessment (LCA), embedded energy calculations, supply chain analysis or energy return on investment (EROI) among others (Deng & Tynan, 2011).

One of these methods is the well-known ***Energy Return on Energy Invested (EROI)*** that measures the energy efficiency of a system. According to Murphy & Hall (2010), the main point of evaluating the EROI of a given energy supply system is the same as for a financial analysis of different investments.

This analysis lets us compare different energy transformation platforms in order to make informed investments decisions for obtaining a profit. This profit for the society as a whole, in energy terms is the net energy (N), which as it can be seen in Equation 1, it depends on the EROI and the rate of energy production (P). Equation 2 shows the net energy to economy (N/P), which is the net energy returned to the economy as a percentage of the total energy produced. This value is essentially a measure of the prosperity for a society, meaning that the value of N/P will be the percentage of energy returned to the economy as a useful energy production from all the energy and resources used by the energy sector.

$$N = P - (S_1 + S_2) = P\left(1 - \frac{1}{EROI}\right) \qquad \text{Equation 1}$$

$$N/P = 1 - \frac{1}{EROI} \qquad \text{Equation 2}$$

Where:

- N is the net energy yield (kWh/analysis period)
- P is the rate of energy production (kWh/analysis period) from the transformation system
- S1 is the conversion energy input (kWh/analysis period)
- S2 is the embodied energy in the various items used by the production system (kWh/analysis period)

Referring to Hall, Lambert & Balogh (2014) work, most energy scientists agree that when more money is required, more energy is required too, so there is a limit to how much we can pay for energy, for example, using a barrel of oil for extracting a barrel of oil.

Therefore, the EROI is the ratio between the energy delivered by a particular source of energy to society and the energy invested in the capture and delivery of this energy as it can be seen in Equation 3. To sum up, it is calculated by putting all inputs and outputs into energetic terms so the evaluation is more straightforward and the result can be interpreted in terms of the general potential for prosperity of the economy.

$$EROI = \frac{P}{S_1 + S_2} = \frac{ER}{EI} \qquad \text{Equation 3}$$

Where:

- P is the rate of energy production (kWh/analysis period) from the transformation system

- S1 is the conversion energy input (kWh/analysis period)

- S2 is the embodied energy in the various items used by the production system (kWh/analysis period)

- ER is the energy returned to the society, the amount of usable energy delivered from a particular energy resource (kWh/analysis period)

- EI is the energy invested in the process, the amount of usable energy used to obtain the energy resource (kWh/analysis period)

Figure 2-7 illustrates a simplified scheme of the life cycle of an energy system divided into its different stages (construction, operation and decommissioning). While energy inputs may occur in every stage, the outputs will usually occur only during the operational phase.

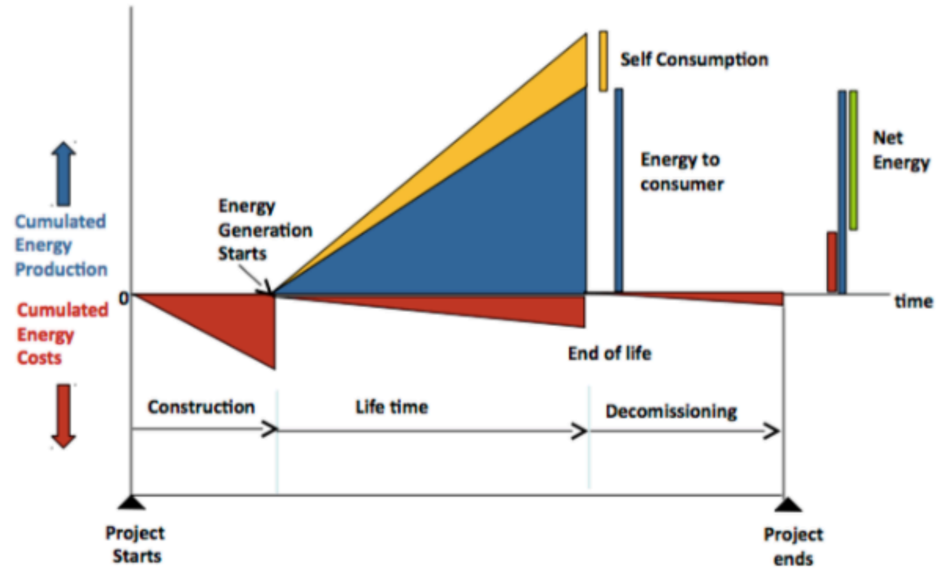


Figure 2-7. Simplified scheme for an energy system
Source: Energy Matters (http://euanmearns.com/eroei-for-beginners/)

Four categories of EROI can be distinguished according to the boundaries set in the study:

1. Standard EROI: This category of EROI divides the energy output for a project by the sum of the direct and indirect energy used to generate that output. However, it does not include the energy associated with the supporting labor, financial services and the like. Therefore, it only takes into account up to the point where it leaves the material extraction and production facility (Murphy, Hall, Dale, & Cleveland, 2011).

2. Point of use EROI: This is a more comprehensive EROI that includes the costs associated with refining and transporting the material. As the analysis has expanded, the energy costs of getting to that point have increase leading into a reduction in the EROI (Hall, Balogh, & Murphy, 2009).

3. Extended EROI: This analysis considers the energy required to get plus the energy required to use a unit of energy. Therefore, it will measure the consumption of that energy in the society (Hall et al., 2009).

4. Societal EROI: This is the overall EROI that might be derived for all society by summing all gains from the source and all costs for obtaining it (Lambert, Hall, Balogh, Gupta, Arnold, 2014).

Consequently, when analyzing an energy system through EROI is important to set the boundaries of the analysis as it will have a significant impact in the final value of the EROI. EROI is the underlying determining factor for prosperity as is an indication of the availability of energy to meet demand and to provide the surplus needed for maintenance, replacement and new manufacturing and construction. According to Figure 2-8, when the value of the EROI drops below 5, then the useful available energy decreases precipitously, that means that low EROIs are linked to obtaining energy at a high cost. However, as it has been explained in this chapter, nowadays the world is in a situation where the levels of CO_2 have to be reduced, therefore policymakers and financial arrangements are put in place to enable deployment of sources with free green house gasses (GHG) emissions as the global energy system is now dictated by the climate concern regardless of the EROI (Hall, Lambert & Balogh, 2014).

Figure 2-8 also depicts the relationship between the ratio of net energy to the rate of energy production and the EROI showing that the lower EROI, the lower available energy (blue area) and the higher energy invested (red area) is needed for generating that source of energy. However, society cannot rely on sources with EROIs lower than 5, that means a N/P = 80% that implies that 80% of the energy consumed is returned to the society as a useful energy production and 20% is consumed in the process and not returned to the economy. The system cannot afford using that amount of energy in generating energy for society because the available energy is also needed for infrastructure, capital projects, mining and manufacturing, agriculture, food processing, education, healthcare, welfare…

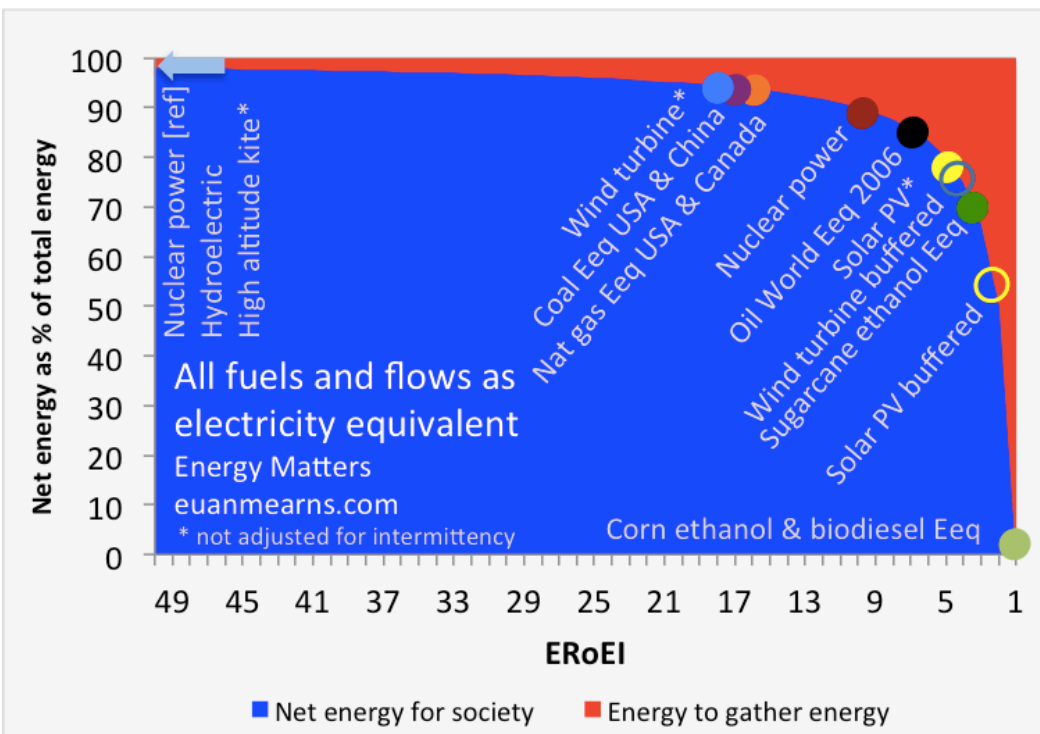


Figure 2-8. Ratio of net energy to the rate of energy production vs. EROI

Source: Energy Matters (http://euanmearns.com/eroei-for-beginners/)

If we continue to embrace technologies that expend too large a portion of our energy endowment to simply get the energy we need to survive, then human society will perish. (Weißbach et al., 2013). Improving efficiency is the key to balance the amount of resources used for obtaining energy free of emissions while using low amount of energy (high EROI) to get it.

2.3 Energy use in industry: Battery Industry

According to World Bank (2014) data, globally, industry accounts for about 29% of final energy consumption and about 23% of the world's workforce (724 million jobs worldwide). Improvement in energy efficiency is needed in all sectors but targeting industrial energy consumption offers major advantages for policy makers because it is more concentrated in terms of entity numbers and often a small number of big energy-intensive enterprises consume the majority of energy in the sector.

The Pareto Principle (also known as 80/20 rule) generally applies to this sector, in that about 20% of industrial sites often consume 80% of the energy used by all of industry. Nearly two thirds of all industrial energy consumption is accounted for by just four sectors: chemical & petrochemical (33%), iron and steel (17%), cement (9%), and pulp and paper (5%) as Figure 2-9 shows (IEA, 2008). Achieving improved energy efficiency in industry can make a significant contribution to solving local, national and global energy problems (Fawkes, Oung & Thorpe, 2016, p. 13).

As it has been corroborated, improving the energy efficiency of industry should be prioritized as it consumes a large proportion of total energy. According to Figure 2-9, since a large proportion of energy use is consumed within a few industrial sub-sectors, making improvements to the energy efficiency in industry would be easier compared to other sectors where energy is often dispersed.

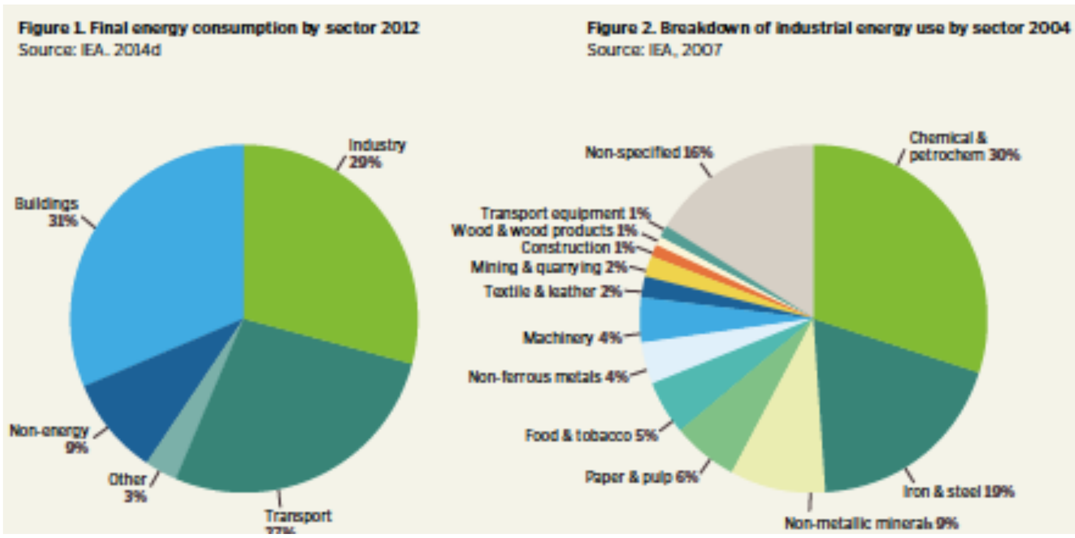


Figure 2-9. Final energy consumption by sector in 2012 and Breakdown of industrial energy used by sector in 2004
Source: IEA. 2014d and IEA. 2007.

One of the industries within this few subsectors (chemical) is the battery industry which it has been gaining relevance these last decade and is making a huge impact in the world's market. Optimizing energy use in battery manufacturing will be advantageous for reducing the amount of energy used in the process leading into the achievement of a more sustainable system (being more ecofriendly and reducing economic costs) creating a product designed from an energy efficient process and making renewable energy available for the market through storage. The most popular way of storage, which is likely to change the future, is using batteries in EVs (Dinger et al., 2010).

CHAPTER 3

BATTERY INDUSTRY ENERGY USE AND EFFICIENY

Chapter 3 discusses energy use and efficiency strategies in battery. There is a discussion in the evaluation of the energy invested in the supply chain and manufacturing of the batteries. This industry was selected due to the vital role batteries could play in successful utilization of the renewable energy systems (also as efficient use of non-renewable carbon-based energy). This chapter is devoted to providing an analysis of the battery technology/industry and estimation of the energy use/invested in in manufacturing of the batteries. Information provided in this chapter is then utilized in chapter 4 when analyzing the application of the batteries as distributed sources of the renewable energy in Smart Grids.

3.1 Technology and types of batteries

According to Crompton (2000), electricity cannot be stored, but electrical energy can. A battery is a device that is able to store electrical energy in the form of chemical energy, and convert that energy into electricity. This device consists of one or more electrochemical cells with external connections provided to power electrical devices such as smartphones or electric vehicles among others.

As Canis (2011) stated in his work, all battery technologies have two fundamental characteristics that affect their design, production, cost of operation, durability and performance:

- **Power density,** which is the amount of energy that can be delivered in a given period of time. This characteristic is related to how fast a vehicle can accelerate.
- **Energy density,** which is the capacity of energy storage. This characteristic is linked to the range a vehicle can travel.

The selection of the battery type will depend on the specific levels of power and energy density required by the battery application. As Suga et al. (2007) explain, there are two types of battery according to the energy use: Chemical batteries or Physical energy batteries (solar, nuclear and thermal). This project will only study the case of chemical batteries as they are the battery type more common used in the world, therefore, the type that would make a greater impact if improving its efficiency. Chemical batteries can be classified in being either Primary or Secondary:

Primary batteries are the well-known disposable batteries; they will produce electricity until they run out of reactants, they are designed to be used until exhausted of energy. These batteries only work in one direction, transforming chemical energy into electrical energy (chemical reaction not reversible), that means that they cannot be recharged.

Secondary batteries, on the other hand, can be recharged. The chemical reaction can be reversed by applying electric current to the cell, regenerating the original chemical reactants. Therefore, these batteries can be used again multiple times. However, secondary batteries are not indefinitely rechargeable because of the dissipation of the active materials, the loss of the electrolyte and the internal corrosion.

Table 3-1. Primary batteries and their characteristics

Source: https://en.wikipedia.org/wiki-/Battery_(electricity)#Principle_of_operation

Chemistry	**Anode (-)**	**Cathode (+)**	**Max. voltage**	**Nominal voltage (V)**	**Specific energy (MJ/kg)**	**Comments**	**Shelf life at 25ºC, 80% capacity (months)**
Alkaline	Zn	MnO2	1.5	1.15	0.4-0.59	Moderate energy density. Good for high and low drain uses.	30
Mercury oxide	Zn	HgO	1.34	1.2		High-drain and constant voltage. Banned in most countries because of health concerns.	36
Silver-oxide	Zn	Ag2O	1.85	1.5	0.47	Very expensive. Used only commercially in 'button' cells	30
Zamboni pile	Zn	Ag or Au		0.8		Very long life. Very low current.	>2,000
Zinc-air	Zn	O2	1.6	1.1	1.59	Used mostly in hearing aids.	
Zinc-carbon	Zn	MnO2	1.6	1.2	0.13	Inexpensive.	18
Magnesium	Mg	MnO2	2.0	1.5			40
Lithium (Li-(CF)n)	Li	(CF)n	3.6	3.0			120
Lithium (Li-CrO2)	Li	CrO2	3.8	3.0			108
Lithium (Li-CuO)	Li	CuO	1.7			No longer manufactured. Replaces by silver oxide batteries.	
Lithium (LiFeS2)	Li	FeS2	1.8	1.5	1.07	Expensive. Used in \`plus\` or 'extra' batteries.	337
Lithium (LiMnO2)	Li	MnO2	3.0		0.83-1.01	Expensive. Used only in high-drain devices or for long shelf-life due to very low rate of self-discharge. 'Lithium' alone usually refers to this type of chemistry.	
Nickel oxyhydrocide			1.7			Moderate energy density. Good for high drain uses.	
Zinc-chloride			1.5			Also Known as 'heavy-duty'. Inexpensive.	

Table 3-2. Secondary batteries and their characteristics

Source: https://en.wikipedia.org/wiki-/Battery_(electricity)#Principle_of_operation

Chemistry	Cell voltage	Specific energy (MJ/kg)	Comments
NiCd	1.2	0.14	Inexpensive. High/low-drain, moderate energy density. Can withstand very high discharge rates with virtually no loss of capacity. Moderate rate of self-discharge. Environmental hazard due to Cadmium – use now virtually prohibited in Europe.
Lead-acid	2.1	0.14	Moderate expensive. Moderate energy density. Moderate rate of self-discharge. Higher discharge rates result in considerable loss of capacity. Environmental hazard to Lead. Common use – Automobile batteries.
NiMH	1.2	0.36	Inexpensive. Performs better than alkaline batteries in higher drain devices. Traditional chemistry has high energy density, but also a high rate of self-discharge. Newer chemistry has low self-discharge rate, but also approximately 25% lower energy density.
NiZn	1.6	0.36	Moderately inexpensive. High drain device suitable. Low self-discharge rate. Voltage closer to alkaline primary cells than other secondary cells. No toxic components. Newly introduced to the market (2009). Has not yet established a track record. Limited sixe availability.
AgZn	1.86	0.46	Smaller volume than equivalent Li-ion. Extremely expensive due to silver. Very high energy density.Very high drain capable. For many years considered obsolete due to high silver prices. Cell suffers from oxidation if unused. Reactions are not fully understood. Terminal voltage very stable but suddenly drops to 1.5 volts at 70-80% charge. Is being developed once again as a replacement for Li.ion
Lithium ion	3.6	0.46	Very expensive. Very high energy density. Very low rate of self-discharge. Very common in laptop computers, moderate to high end digital cameras and cellphones. Require user awareness or a management system to slow down the gradual loss of capacity. Terminal voltage unstable (varies from 4.2 to 3.0 volts during discharge). Volatile: Chance of explosion if short-circuited, allowed to overheat, or not manufactured with rigorous quality standards.

Table 3-1 and 3-2 show the most used batteries and its characteristics according to the type of material used and its classification, whether they are primary or secondary (Van den Bossche, Vergels, Van Mierlo, Matheys & Van Autenboer, 2006).

3.2 Application of the batteries in the energy field

Batteries are an energy storage solution designed to store electricity. They store and release energy through electrochemical processes. Two actions in energy storage can be distinguished according to where the electricity comes from (grid or renewables) and the period when energy is stored (off-peak hours or at any time).

Following this idea, two types of battery storage can be differentiated: Grid battery storage and Renewable Energy (RE) battery storage. Both types are meant for taking advantage of the electrical demand and the electricity prices (Crabtree et al., 2011).

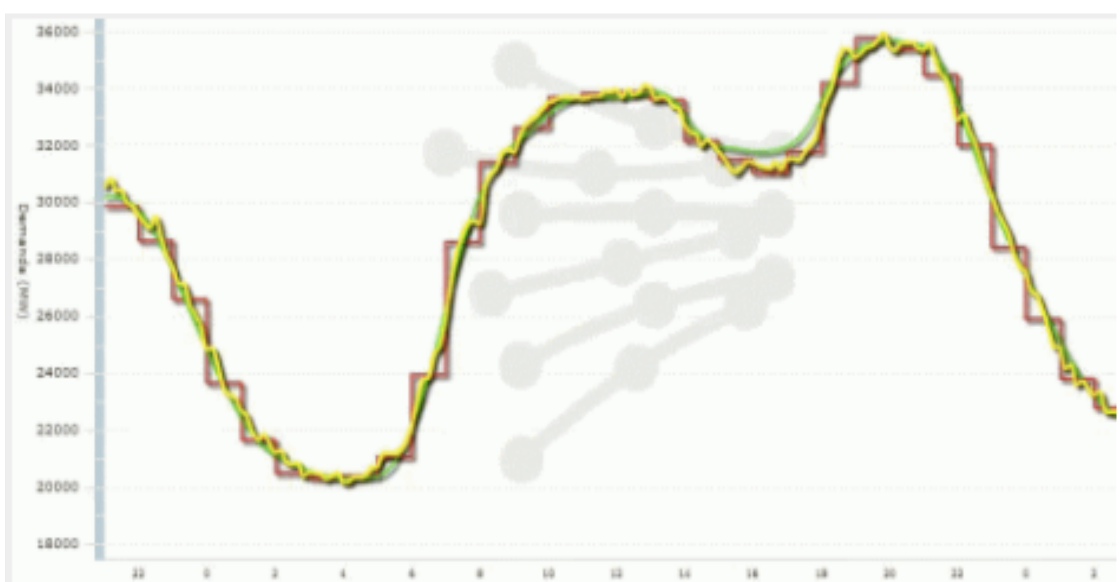


Figure 3-1. Demand of electricity in a day

Source: Antonio Narejos (https://antonionarejos.wordpress.com/tag/energia/)

As it can be seen in Figure 3-1, the curve of consumption during a day is related to the cost of electricity, the higher period of consumption will be the higher price of electricity. This shape in electricity consumption varies between countries and seasons in order that each country has its own schedules as well as its own weather.

3.2.1 Batteries for grid energy storage

Grid battery storage is used to store electricity during off-peak hours, when rates are low, and use it in peak hours, when rates are higher. In other words, shift the electricity use from peak hours to off-peak hours in order to take advantage of energy cost (Armand & Tarascon, 2008). This storage method is the same one used by hydro energy, which pumps water at night when energy is cheap in order to sell the energy generated by the turbines during peak hours when the demand and the price of energy are higher for, among others, making profits/income (Yang & Jackson, 2011).

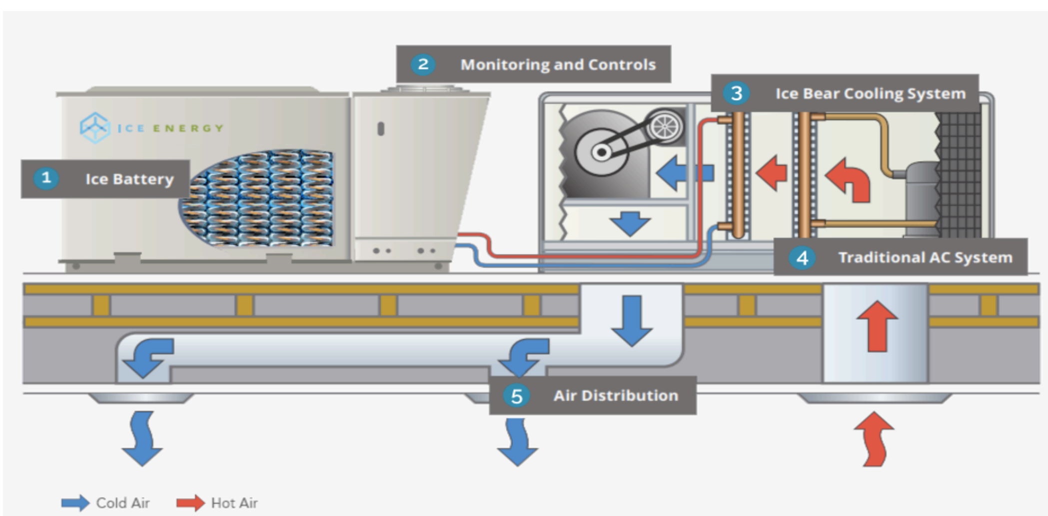


Figure 3-2. Ice bear 30 (designed for industrial application)
Source: Ice Energy (https://www.ice-energy.com/technology/)

When the goal is to store energy from the grid, ice battery linked to a cooling system is an innovative energy storage solution. When electricity demand is off-peak hours and energy costs are low, the energy-intensive AC compressor starts producing ice, which will be stored. Once demand starts to peak and energy prices starts to rise, the unit turns off the AC compressor and uses the ice stored to provide cooling. These systems reduce not only the cooling costs by up to 40% but also there is a reduction between 8% and 30% in the source fuel needed to generate the same amount of energy. Not only that but also they use 5% of the power that otherwise would have been required, lowering cooling bills and reducing carbon emissions. Figure 3-2 is a representation of the Ice bear 30, which as it can be seen; it has the ice batteries component as well as the AC system and depicts the flow of hot and cool air (Ice Energy, 2005).

3.2.2 Batteries for renewable energy storage

Renewable energy battery storage are the batteries designed for storing the extra amount of electricity generated from renewables and taking advantage of the electrical demand and the electricity prices linked to it. Their purpose is to store the excess of energy produced during the day as well as during the night. This type of batteries takes advantage of the extra amount of renewable energy produced instead of sending it to the grid. This is the energy that is not injected into the grid because there is an excess over the demand. The RE battery storage will not only use energy that otherwise would be wasted but also will allow the use of more renewable energy in the electric market that results in the reduction of the consumption of other non-environmentally friendly fuels (Dunn, Kamath & Tarascon, 2011).

The main drawback of renewable energy (RE) is that it is a random energy, which means that it is unpredictable. Renewables don't assure a steady supply of energy that can meet the electrical demand. The most common RE are both wind and solar, however, electric demand cannot depend on intermittent supply. While wind tends to produce more energy at night (off-peak hours), solar can only generate electricity during peak hours. That is why utilities have to build extra capacity just to meet occasional demand peaks; the US for example, typically uses less than 30% of the installed capacity (Kobos, Erickson & Drennen, 2006).

According to Carrasco et al. (2006), that problem can be solved thanks to batteries which are able to store power during periods of low demand (off-peak hours or extra energy during peak hours), instead of waste it, in order to release it whenever is required letting green energies be competitive in the market against fossils fuels and saving a significant amount of money on capital costs. Not only that but batteries for RE energy also can smooth out frequency variations and provide voltage support.

This is the case of super large batteries for grid storage that can store large amounts of energy from huge renewable energy installations and smaller batteries than can store energy from smaller renewable energy installations such as the ones in off-grid/self supply houses.

3.2.3 Batteries as distributed source of energy: The Battery Electric Vehicles (BEVs)

The Battery Electric Vehicles (BEVs), according to its basic function would be classified as grid battery storage as they can store energy (battery charge) during night when the electricity is cheaper and use it during the day while using the vehicle (battery discharge) taking advantage of electricity cost during off-peak hours. However, regarding Karamitsios (2013) study about Tesla Motors vision, BEVs should be designed for being linked to an off-grid house. As it can be seen in Figure 3-3, the main battery that would charge the car at night would not use the energy that comes from the grid but from a secondary battery installed in the house that would have stored the electricity generated in the RE system of the house during the whole day (sun and wind energy). Therefore, BEVs would be in the end a RE battery type according that energy has been generated by RE at first instance.

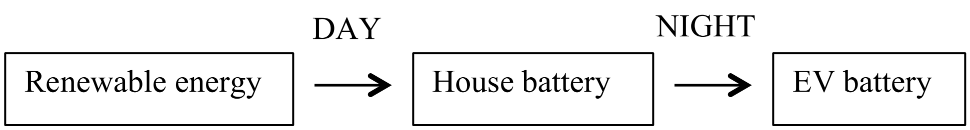


Figure 3-3. EV batteries linked to house batteries scheme

Batteries will eliminate the need for high-priced peak power, boost grid resiliency and increase efficiency. Not only will be achieved a reduction of the costs by using low-priced kWh but also there will be a reduction in the source fuel and carbon emissions needed to generate the same amount of energy. Batteries are the solution for a clean, reliable and least-cost distributed energy storage for the grid (Karamitsios, 2013).

3.3 Electric Vehicle role: Battery as storage/source of energy for Smart Grid

Promotion of electric vehicles and the batteries to power them is part of a federal effort to reduce oil consumption and air pollution. Depending on the source of the electricity, the total carbon footprint of an electric vehicle may be less than that of a vehicle with a traditional internal combustion engine. The major hurdle in providing electric vehicles is the size, cost, weight, durability, and safety of the batteries that would power them.

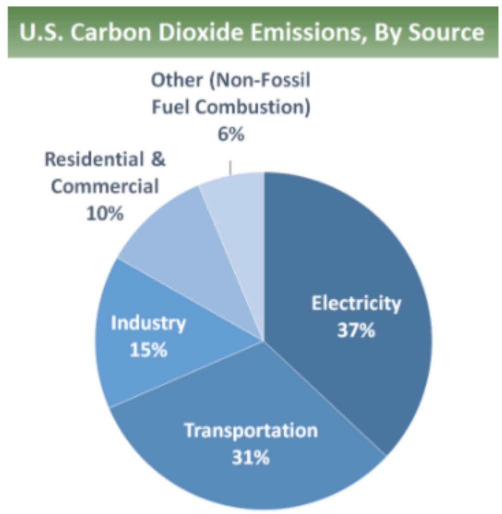


Figure 3-4. U.S. carbon dioxide emissions by source. All emission estimates from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014. Source: United States Environmental protection Agency (https://www.epa.gov/ghgemissions/overview-greenhouse-gases)

Road transportation is one of the sectors that most contribute to the emissions of CO_2, which is the main cause of global warming, as it can be seen in Figure 3-4. Moreover, it is almost entirely dependent on oil-derived fuels and therefore highly vulnerable oil price shocks and supply disruptions. Not only CO_2 emissions but also PM10, NOX and VOCs gasses that are harmful for the human health are emitted in internal combustion engines (Offer, Howey, Contestabile, Clague, & Brandon, 2010).

According to Offer et al. (2010), p. 3, in order to solve these issues in road transport there are solutions such as managing demand or promoting co-modality, however, those are a partial solution. The rest of the solution would be introducing alternative transports fuels and vehicles in order to achieve the objectives of decarbonisation, energy security and urban air quality.

Three alternative powertrain technologies are considered by the International Energy Agency (IEA) as being capable of delivering a sustainable road transport system with near zero emissions (IEA, 2008): Battery Electric Vehicle (BEV), hydrogen Cell Fuel Electric Vehicle (FCEV) and finally the biofuels, which unlike the other two, is not based on electric drive trains.

Referring to King (2007) and King (2008), the electric vehicle has the potential to decarbonize road transport in the UK by 2030, from 80g CO_2 km^{-1} could be reduced to 30g CO_2 km^{-1} in the period of 13 years. A prediction that includes: increased renewables, nuclear and the use of carbon capture and storage with coal.

On the other hand, the project of HyWays (2008) stated that if 80% of the road vehicles were hydrogen-fueled by 2050, this would result in 50% less CO_2 emissions in the EU. Both studies demonstrate the potential of electricity and hydrogen as fuels to significantly contribute to the carbonization in transport.

Therefore, here is the solution for breaking the link between oil and transport and improve energy security, according that both electricity and hydrogen can be produced from renewable sources such as wind, solar, biomass, nuclear or decarbonized fossil fuels among others (Offer et al., 2010).

If we are not in this scenario in the actuality is because of the various barriers to the widespread adoption of Battery Electric Vehicles and Cell Fuel Electric Vehicles, which are basically, to be the issues we face in technical, economic and infrastructural domains. A typical private vehicle is a complex consumer product, which has to be optimized for multiple performance criteria such as peak power (acceleration), average power (cruising efficiency) and energy density (range).

On the one hand, a Battery Electric Vehicle is capable of delivering peak power and average power at excellent efficiency but has the problem in the battery technology, specifically on the low energy density (range) that means that batteries are large, heavy and expensive. On the other hand, a Cell Fuel Electric Vehicle is capable of delivering average power at higher efficiency than Internal Combustion Engines and like them, the range is determined by the size of the tank. But the problem is that when delivering peak power, the fuel cell must be large and therefore expensive (Tollefson, 2008).

In order to reduce costs, massive production will partly provide a solution for both Battery Electric Vehicles and Cell Fuel Electric Vehicles. The rest of the solution may come from the improvement in technology; smaller and cheaper batteries and a riskless infrastructure for transmitting and refueling hydrogen have to be developed (Charters, 2008).

However, there is a transition from Internal Combustion Engine Vehicles (ICEVs) to Battery Electric Vehicles (BEVs) and Cell Fuel Electric Vehicles (FCEVs) just mentioned. Nowadays, we are in this transition that means, that the vehicles are currently found in the roads in larger amounts are the Hybrid Electric Vehicle (HEV) and the Plug-in Hybrid Electric Vehicle (PHEV), which unlike HEV, the electricity is not obtained from internal electric systems but also from plugging in the vehicle to the grid.

3.3.1 Future of the Electric Vehicle

It is difficult to predict the future of the vehicles that will be in our roads as also depends on the technological advances, fuel prices and the subsidies provided by governments.

Nonetheless, what is certain is that electricity, hydrogen and biofuels will replace fuel oil thanks to Battery Electric Vehicles run by electricity, Cell Fuel Electric Vehicles run by hydrogen and Plug-in Hybrid Electric Vehicles and Hybrid Electric Vehicles run by both electricity and biofuels. In 2010, BEVs and FCEVs were far more costly than conventional Internal Combustion Engine Vehicles.

However, by 2030 capital costs for EVs will drop significantly (BEVs will be cheaper than FCEVs) at the time that fossil fuels prices will start to grow making the difference wider that will lead into the era of electricity and biofuels as the new vehicle fuel.

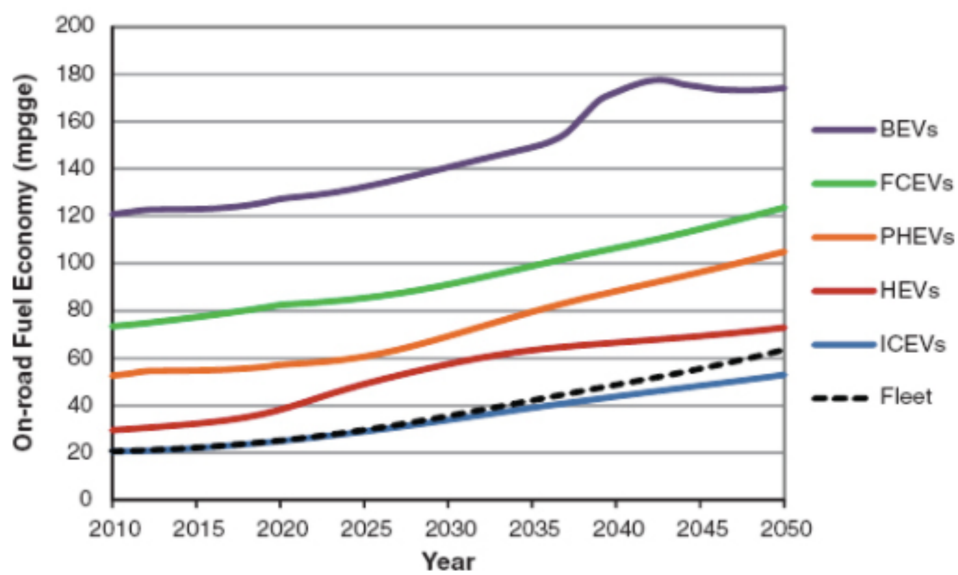


Figure 3-5. Annual evolution of on-road fuel economy measured in miles per gallon gasoline equivalent (mpgge) according to the different types of vehicles
Source: National Research Council. (2013)

Figure 3-5 shows the annual evolution of on-road fuel economy measured in miles per gallon gasoline equivalent (mpgge) according to the different types of vehicles used, which the efficiency of each topology can be extrapolated. Therefore, it seems that BEVs will be the most efficient method of road transport in the future (National Research Council, 2013).

The main challenge of EVs is the insufficient range and power of electric car batteries compared to gasoline engines. Furthermore, electrics cars are significantly more expensive than gasoline ones. However, nowadays, battery technology has certainly improved and a lot of research and development is being done on battery technology to improve its performance while ensuring that batteries are lightweight, compact and affordable.

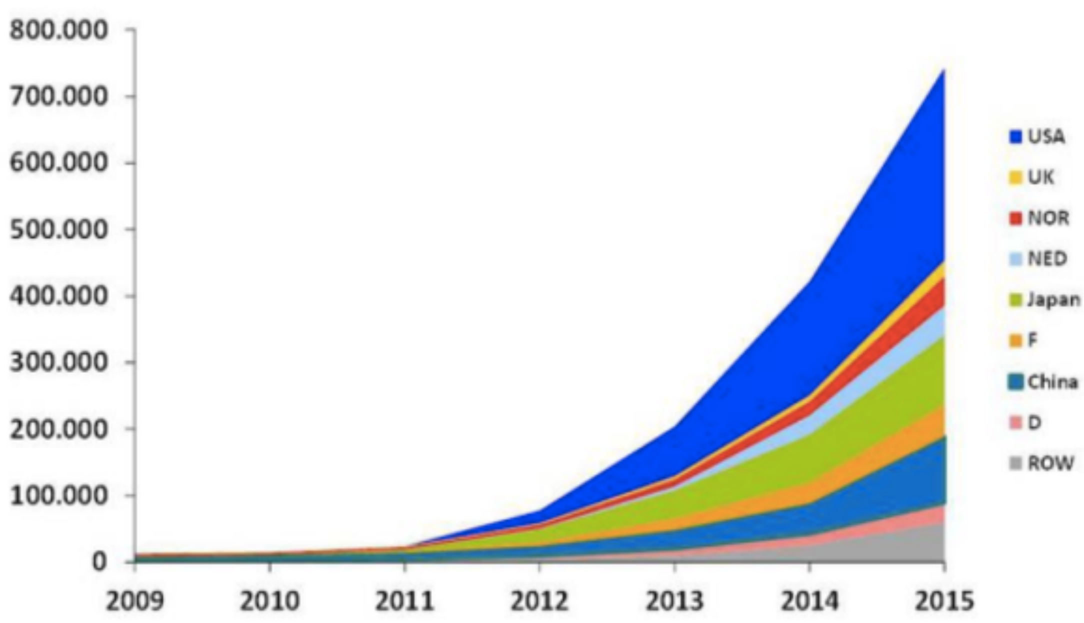


Figure 3-6. Demand for electric vehicle from 2009 to 2015

Source: Clean Technica (https://cleantechnica.com/2015/03/28/ev-demand-growing-global-market-hits-740000-units/)

Figure 3-6 shows the evolution of sales of EVs in the market, that is the number of EVs found in the roads, which as it can be seen it has experienced a huge increase in the last years reaching in 2015 a demand of 740,000 units (Ayre, 2015).

3.3.2 Future of the battery in the Electric Vehicle

According to Canis (2011), p. 5, for the last years, the lead-acid batteries have been the leaders in the vehicle field, however, since 1970, researchers have sought better battery technologies given their shortcomings. One of the alternatives has been the nickel metal-hybride (NiMH) battery, which has become the choice for early hybrid vehicles due to its grate energy density and its low weight. A second alternative has been the improvement of lead-acid batteries, which thanks to federal research grants, the U.S. lead-acid battery manufacturers have developed the use of lead-carbon for an 'ultrabattery' that will probably replace NiMH with a more efficient, lower-cost alternative (Kempton & Letendre, 1997). A third technology is the 'Zebra' battery, which uses sodium-nickel chloride chemistry to produce 50% more energy than the one produced by NiMH batteries and can reach the levels of lithium-ion batteries. This type of battery performs well in both very hot and very cold climates.

There are five emerging battery technologies for electric vehicles, which are considered the newest innovations in battery technology and will imply significant advances for the electric vehicle market.

- **Lithium-ion batteries** (LIBs) are currently the most used battery for electric vehicles, and it seems that they will remain dominant the next decade. One of the main advantages of this type of battery is its high cyclability that is the number of times the battery can be recharged without losing its efficiency. Li-ion batteries have high energy and power densities because that makes it highly suitable for electric vehicles applications. Since lithium is a lightweight metal, it can be fabricated into large battery packs. Not only that, but also lithium is reusable and can be extracted from depleted batteries and recycled for use in new batteries. One of the drawbacks of this technology is the bad reputation garnered because overheating and catching on fire. That is why manufacturers have to work for make them more stable and developing mechanisms to prevent harm if the battery set on fire. These batteries are being used by companies such as Nissan and Tesla Motors (Yoshio, Brodd & Kozawa, 2009).

- **Solid-state batteries** are known for having solid components, which lead into a series of advantages. It does not have to worry about the electrolyte leaks or catching on fire, they have an extended lifetime, decreased need for bulky but expensive cooling mechanisms, and the ability to operate in an extended temperature range. These batteries are being looked into by companies such as Toyota and Volkswagen (Kurt, 1954).

- **Aluminum-ion batteries** are quite similar to lithium-ion batteries but with an aluminum anode. These types of battery are still under development and research but it is believed that they will increase safeness at a decreased cost over LIBs (Jayaprakash, Das & Archer, 2011).

- **Lithium-sulfur batteries** are characterized for having a lithium anode and a sulfur-carbon cathode. Unlike LIBs, they offer a higher theoretical energy density in a lower cost. However, the major drawback is their low cyclability caused by expansion and harmful reactions in the electrolyte. This type of battery is being used in several projects developed by NASA (Nazar, Cuisinier & Pang, 2014).

- **Metal-air batteries** are known for having a pure-metal anode and an ambient air cathode. The major advantage of this type of battery is the weight in order that the cathode usually is the heavier component, in this case is made of air. The typical metal used is lithium, aluminum, zinc or sodium whereas the cathode can be air or oxygen in order to prevent the metal from reacting with CO_2 in the air. However, for the moment these batteries present problems with lifetime and cyclability (Lee, 2011).

Electric vehicles will undoubtedly become more commonplace as batteries improve. The revolution and advancement in the battery field will not only change the transportation industry but also they will transform significantly the global energy market according that the combination of batteries and renewables resources will lead into the reduction of fossil fuels dependency altering economic and political norms. Those changes can be seen these recent years with just little advances in battery technology, therefore, with the exponential growth in technology advancements, changes and impact in the world will be exponential too (Thomas, 2009).

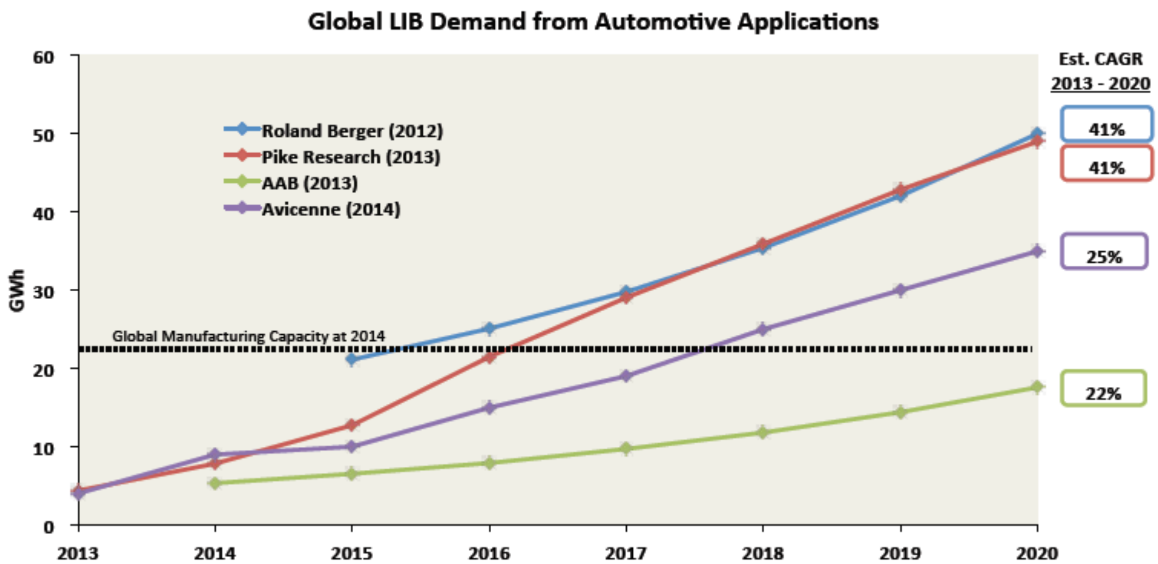


Figure 3-7. Global LIB demand from automotive applications

Source: Berger, R. (2012), Pike Research (2013), AAB (2013), Avicenne Energy (2014)

Among all the types of batteries used, according to Figure 3-7, the one that is being more popular and has better future perspectives with most prominent major new battery technology is the lithium-ion battery, which is being more used every day among the world's leading vehicle companies in their latest electric models.

CHAPTER 4

LITHIUM-ION BATTERY: ENERGY MANAGEMENT IN BATTERY MANUFACTURING

Chapter 4 introduces the operation and supply chain of lithium ion battery industry, energy use, its advantages and disadvantages, the challenges of this technology, the market situation and the future perspectives. There is also and overview of the structural components and the principle of operations of the battery as well as its supply chain and manufacturing processes.

4.1 Lithium-ion battery

Lithium-ion batteries are the fastest growing type of battery in the market and most promising battery chemistry. These batteries are characterized by being rechargeable (secondary batteries type) and being made of lithium, the lightest of all metals and the one with greatest electrochemical potential (high voltage) providing the largest energy density for weight, meaning that batteries can provide large amounts of energy in less space (capacity) and being lighter compared to other battery types (Poole, 2013). As seen in Table 3, lithium-ion batteries are the ones with higher voltage meaning that they have high power density as they can deliver instant energy in a short period of time as well as they can be recharged faster.

Lithium-ion batteries provide both high power density and high energy density, which in the case of the electric vehicles (EVs), is the optimum scenario as it lets the battery compete with the gasoline engine. Battery alternatives to gasoline power have not achieved this parity and are heavy, large in size and expensive. However, the technological breakthroughs plus the evolving in the electric market are letting batteries enter to the market.

4.1.1 Lithium-ion battery advantages and disadvantages

According to Messina (2015), among the several advantages of using this type of batteries, the most important ones and the ones that makes lithium-ion batteries the most suitable battery for EVs are aside from providing high energy and power density, the low maintenance as there is no memory and no scheduled cycling is required to prolong the battery's life and the self-discharge is relatively low. The fact that there is a wide variety of types of lithium ion cells available imply that the most suitable technology can be used for the particular application needed providing the best performance.

However, this battery also present some drawbacks such as the need of a protection circuit in order to maintain voltage and current within safe limits, this battery type presents a high risk of exploding. It is also subjected to aging even if the battery is not in use as well as metals and chemicals changes on a continuing basis because the technology is not mature.

Nevertheless, the main restriction of the battery is that it is expensive to manufacture. Batteries alone are estimated to cost from \$8,000 to \$18,000 per vehicle, more than 50% of its total value comes from the battery itself. Its development is likely to depend heavily on foreign competition and how the federal government further addresses the challenges of building a battery supply chain and promoting advances in battery technologies (Bonheur, 2016).

4.1.2 Lithium-ion battery applications

Lithium-ion batteries are well known for being used in consumer electronics (CE) applications such as cellphones or laptops. According to Figure 4-1, the majority of the demand for LIBs is driven and may continue to be driven by CE applications. However, automotive demand is expected to grow as well as the use of batteries for grid storage. This increase is affecting the LIB market significantly placing this type of battery technology in first place among the leading technologies in the battery market (Chung et al., 2015).

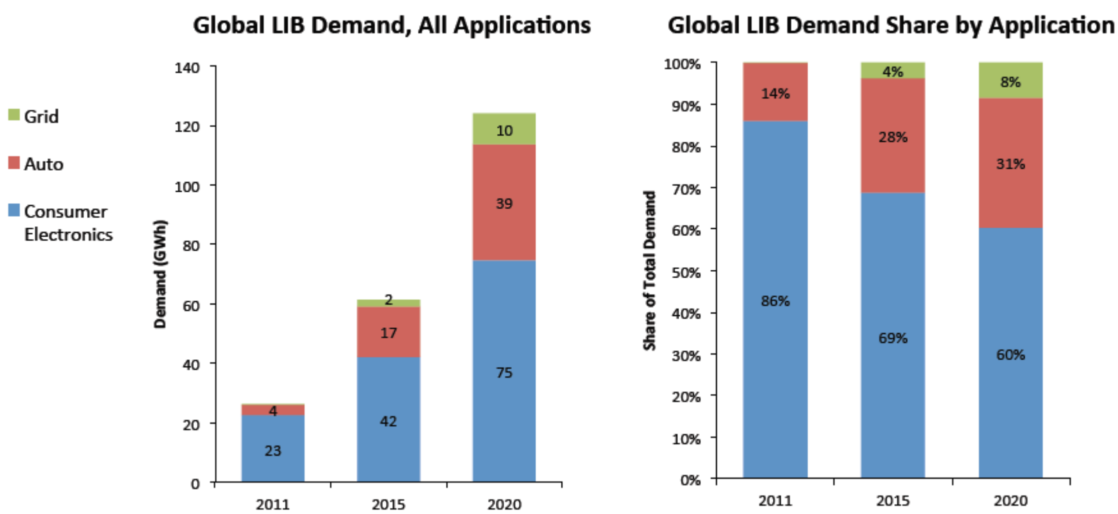


Figure 4-1. Global LIB demand for application

Source: Berger, R. (2012), Pike Research (2013), AAB (2013), CEMAC analysis

4.1.3 Lithium-ion battery future perspectives

According to Canis (2011), current research emphasizes reducing the cost and improving the performance of LIBs as well as addressing new materials for cathodes, like manganese oxides or iron phosphates among others. These new methods will offer cheaper and more stable alternatives to lithium cobalt oxide, contributing to cost reductions for EVs.

The truth is that the battery industry will grow only as fast as the electric vehicle market. Nearly all automakers are offering some type of electric vehicle and there is a small but dedicated consumer base that is increasingly purchasing this type of vehicles. Electric vehicle sales increased from 2.37% in 2010 to a 3.38% in 2012 by selling more than 434,000 hybrids and more than 52,000 electric vehicles in the US, showing that there is being a significant increase yearly in the EV market (Canis, 2011).

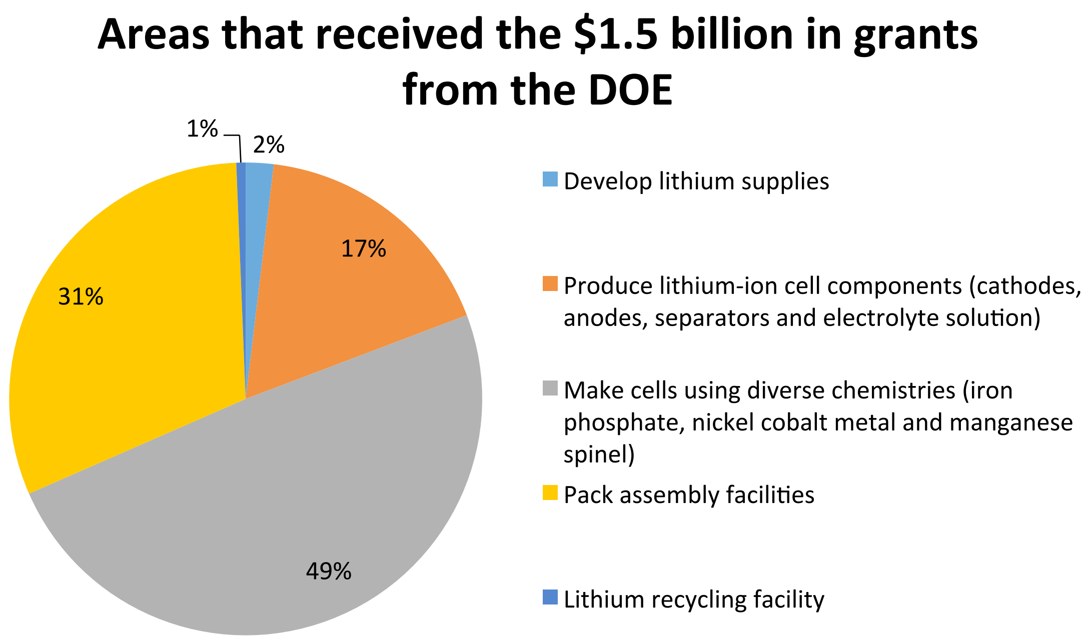


Figure 4-2. Areas that received the $1.5 billion in grants from the DOE
Source: DoE Announces $2.4 Billion for U.S. Batteries and Electric Vehicles," Press Release from U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, August 5, 2009, http://apps1.eere.energy.gov/news/ daily.cfm/hp_news_id=192.

As Chung et al. (2015) stated, the battery supply chain is an important factor in the final battery cost. That is why, governments are offering grants to improve the battery supply chain in their countries. In the case of the US, several grants have been provided from the Department of Energy (DOE) in order to accelerate the development of a domestic battery supply chain with the purpose of reducing the battery cost. Figure 4-2 shows the different areas where the $1.5 billion grant was spent, indicating that the cell making and the pack assembly is a significant process that should be improved in the supply chain of the lithium-ion battery.

The American Recovery and Reinvestment Act of 2009 (ARRA; P.L.111-5) provided financial support to develop a domestic lithium-ion battery supply chain for electric vehicles. The federal government has invested $2.4 billion in electric battery production facilities and $80 million a year for electric battery research and development.

Developing affordable batteries that can offer long driving range is the biggest challenge to increase sales of plug-in electric vehicles. Traditional lead-acid batteries are larger, heavier and more expensive. Lithium-ion appears to be the most feasible approach at the present time. The ARRA would increase US advanced technology battery manufacturing capability from two plants and a 2% global market share to more than 24 manufacturers and a projected 40% of the world's EV batteries by 2015, cutting the cost of batteries in half by 2013. Not only that, but the technological breakthroughs has been another factor that has allowed to reduce the cost of the lithium-ion batteries. Table 4-1 depicts the increase in funding for energy storage research over the recent years. Thanks to both the federal government grants in the supply chain and the R&D in the battery field, the cost of LIB has dropped from $1,000/kWh in 2008 to $500/kWh in 2012 and $300/kWh in 2014 seeking to lower the cost to $125/kWh by 2022 (Energy Storage Research and Development, 2013).

Table 4-1. Recent funding for energy storage research
Source: U.S. Department of Energy Efficiency and Renewable Energy (EERE).
a. FY2013 DOE request.

Annual Appropriations, in Millions of Nominal U.S. Dollars

Fiscal Year	Amount
2002	$24.1
2003	21.6
2004	22.3
2005	22.5
2006	24.5
2007	40.9
2008	48.3
2009	69.4
2010	76.2
2011	93.9
2012	89.9
2013[a]	157.9

In addition to the level of federal support, the following factors will also influence the future of the battery industry related to EVs (Canis, 2011):

- **Cost:** The current cost of EV batteries is too high. Batteries cost from $375-$750/kWh meaning that a 16kWh battery would cost around $12,000. Fully electric vehicles with a longer driving range would require at least 35 kWh meaning that batteries alone would cost more than many vehicles on the road (Chung et al., 2015).
- **Charging:** The charging of an EV depends on the distance driven, however, they are recharged as often as every day. Three different levels of charging can be

distinguished according to the voltage intensity and consequently, the amount of time needed for a full battery charge:

- **Level 1:** 110-volt household current → over 12 hours
- **Level 2:** 240 –volt home charging station → 6 hours
- **Level 3:** 440-volt commercial charging station → 30 minutes

The main issue would be the time spent when charging, the availability of charging stations for EVs and the need of a whole new infrastructure (Yilmaz & Krein, 2013).

- **Range:** Vehicles with electric motors have a shorter range compared to internal combustion engine vehicles, this means that EVs need to be charged more often. Or in other words, that you are not able to travel large distances without refilling (Franke et al., 2012).
- **Price of gasoline:** The price of gasoline would directly affect the demand of fuel-efficient vehicles as they are market competence (Lave & MacLean, 2002).
- **IC engine technology:** As the main competence for EVs, the improve of fuel efficiency in internal combustion engines would reduce this type of vehicle cost leading into a reduction in the attraction of electric vehicles (Lave & MacLean, 2002).
- **Subsidies by other governments:** There is a huge competence among the world's leading countries for being the world's dominant battery manufacturer country. The US is not the only country pursuing the establishment of the lithium-ion battery supply chain. Japan is currently the leader in manufacturing advanced

EV batteries, however, South Korea has announced an investment of $12.5 billion in the battery area and China is already investing $15 billion (Canis, 2011).

4.2 Structural components of Lithium-ion batteries

A lithium-ion battery consists of a number of voltaic cells in which each cell is formed by six main components: two terminals made of different chemicals (the anode and the cathode), the electrolyte solution which separates these terminals, the separator, the durable case and the safety elements for preventing potential chemical leakage and flammability. Figure 4-3 represents the schemes of the components of both a prismatic LIB cell and a cylindrical LIB cell.

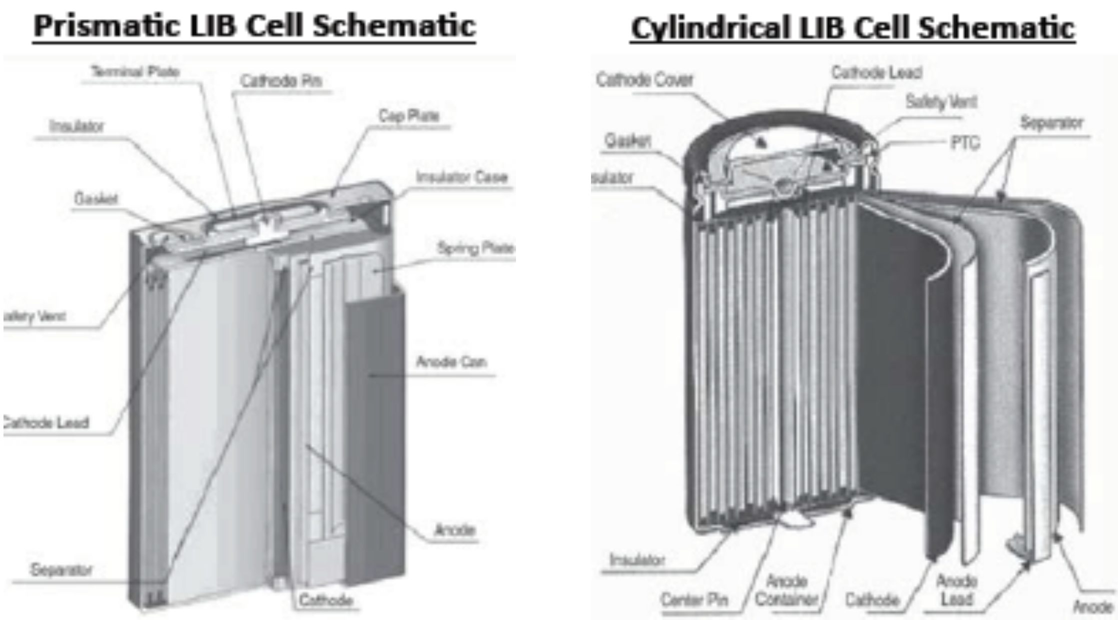


Figure 4-3. Cross section of a prismatic and a cyilindrical Li-ion cell.
Source: Lowe, Tokuoka, Trigg & Gereffi (2010), p. 32.

According to Lowe, Tokuoka, Trigg & Gereffi (2010), p. 31, Li-ion battery cells can also be manufactured in rectangular/prismatic shapes if they use gel as electrolyte, which is encased in laminated films. The rectangular design implies an increase in efficiency as their shape means that a higher number of finished cells can be assembled in a battery pack increasing the density of the battery, these batteries are perfect for smaller devices such as cellphones or laptops according to its effective use of space. However, prismatic cells have a higher manufacturing and designing cost, a shorter life because thermal management is less effective and there are a limited number of sizes, less suppliers compared to cylindrical batteries. What's more, cylindrical takes advantage of its structure by using the free space between cells to install thermal regulation solutions. All this advantages make the cylindrical shape the perfect choice for EVs and grid storage (Messina, 2015).

The main parts of the cell and their functions are the following:

- **Cathode:** This is the chemical located in the terminal that accepts electrons through a reduction reaction, consequently, is the point where the current flows out of the battery.

  Four main types of materials can be used in making the cathode of a Li-ion cell. Regardless of the material, it is pasted on aluminum foil and pressed into a suitable shape and thickness. Despite the different types of chemistries, all of them have similar energy and power densities (Canis, 2011, p. 7).

  Table 4-2 shows the types of cathodes used by the different developers and vehicle application.

Table 4-2. LIB chemistries for cathodes used by developers and vehicle application
Source: Canis (2011)

Some Major Lithium-Based Technologies in the United States

Types of Cathodes	Developers	Vehicle Application
Nickel, cobalt, and aluminum (NCA)	Johnson Controls, Panasonic	Mercedes Benz S400 Hybrid, Tesla Model S
Manganese	LG Chem, NEC	Chevrolet Volt, Nissan Leaf
Iron-nano-phosphate	A123 Systems[a]	Fisker Karma,[b] Chevrolet Spark
Nickel, manganese, and cobalt (NMC)	EnerDel	THINK City electric vehicle[c]

- **Anode:** The anode is the chemical located in the terminal that releases electrons through an oxidation reaction, consequently, is the point where the current flows in from outside the battery. While the cathode type varies from automakers, the material used for the anode is generally graphite and carbon pasted on copper foil and then pressed into shape.
- **Electrolyte:** This is the chemical medium that allows the flow of electrical charge between the cathode and the anode. The electrolyte is a mixture of lithium salt and organic solvents such as methyl carbonate or propylene carbonate. Lithium polymers batteries use a viscous gel as electrolyte to reduce the chance of leaks increasing the mobility of Li-ions to improve battery performance (Chung et al., 2015).
- **Separator:** A porous membrane made of polyethylene or polypropylene whose function is to prevent the anode and cathode from coming into contact whit each other. Not only that but also provides a safety function. When the cell heats up accidentally, it melts down and prevents ion transfer stopping the chemicals reactions (Chung, 2015).

- **Safety elements:** One of the main drawbacks of LIB batteries is that they can overheat which can end up in explosions. Safety elements such as safety vents, thermal interrupts and a center pin to provide structural stability and prevent short-circuit can be found in Li-ion batteries. The reason why LIB batteries are more likely to short-circuit compared to lead-acid or NiMH batteries is because the electrolyte solution is flammable. When a short-circuit is produced, battery temperatures increase by several hundred degrees in seconds, that leads to a chain reaction that could destroy the battery and cause fire. Computer-controlled, liquid thermal cooling and heating system to control temperatures are considered safety elements (Canis, 2011, p. 7).
- **Canister:** Each Li-ion cell is housed by a steel or aluminum can, which are assembled into a battery pack for final use. The battery design varies between automakers, but typically, those battery packs are 6 feet long, it has a weight of 435 pounds and is arranged in a T-shape located under the center of the passenger cabin.

4.3 Principle of Lithium-ion batteries operation

The principle of operation of a lithium-ion battery consists in the Redox reaction (Reduction-oxidation reaction). Figure 4-4 represents a scheme of a LIB during its charge (flow of energy received to the battery) and during its discharge (flow of energy released from the battery).

As Suga, Pu, Kasatori & Nishide (2007) demonstrate in their work, the electrolyte is a chemical medium that allows the flow of electrical charge between the cathode and the anode. According to Figure 4-4 (a), during the discharge of the battery (flow of electrical energy to the connected device) the type of conversion is from chemical energy to electrical energy. In that process two reactions occur: the chemical on the anode releases electrons to the negative terminal and ions to the electrolyte through the oxidation reaction. Meanwhile, in the positive terminal, the cathode accepts electrons completing the circuit for the flow of electrons. Therefore, during the discharge, the anode will be the negative terminal while the cathode will be the positive one, where reduction reaction will take place.

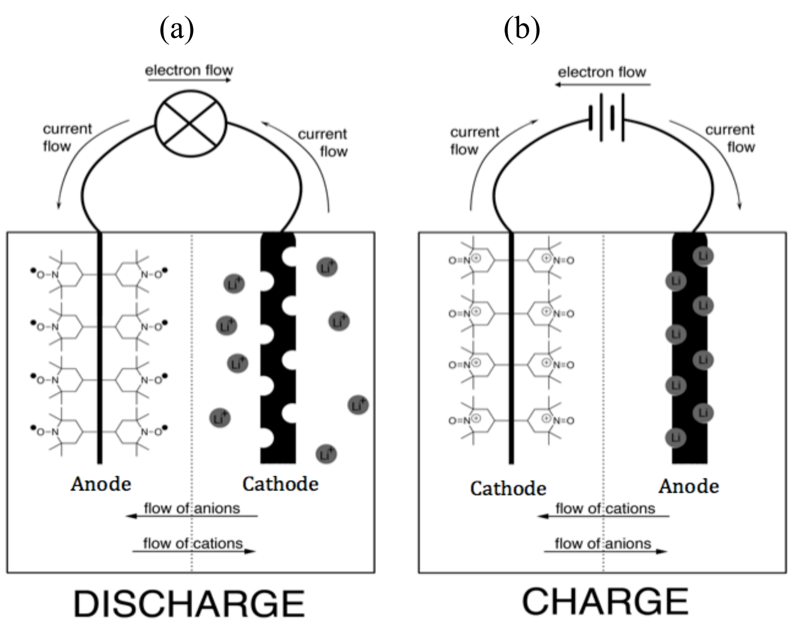


Figure 4-4. Discharge and charge of a hybrid ORB/Li-ion battery
Source: Nakahara, Oyaizu & Nishide (2011)

On the other hand, if the battery is rechargeable, during the charge process (flow of electrical energy to the battery), shown in Figure 4-4 (b), the type of conversion is from electrical energy to chemical energy. In that process it is the again the chemical on the anode the one that releases electrons, but this time, to the positive terminal and ions to the electrolyte through oxidation reaction. At the same time, in the negative terminal, the cathode accepts electrons completing the circuit for the flow of electrons. Consequently, during the charge, the anode will be the positive terminal and the cathode will be the negative one, where reduction reaction will occur (Suga et al., 2007).

4.3.1 Lithium-ion batteries: The Supply Chain

According to Navigant Research (2013), Navigant Research, also known as Pike Research, forecasts that the worldwide market for LIB for vehicles will grow 1375% between 2012 and 2020 (from $1.6 billion to $22 billion). The firm also states that Asia Pacific region supported by the aggressive goals in plug-in vehicle production, the creation of charging infrastructure and incentives for consumer purchases established by their governments, will continue to be the global leader in both Li-ion production and consumption in the transportation industry.

In 2010, 80% share of global production of lithium-ion batteries were held in Japan and South Korea, while 12% of them were produced in China and 6% in the rest of the world, leaving about a 2% for the U.S. However, these numbers will change with the increase in demand that the decade holds. According to Block et al. (2014), 3.8 million electric vehicle annual sales will be reach worldwide by 2020 letting the U.S. have a more significant role in the LIB supply chain.

If the demand of EV reaches the estimated and forecasted numbers, the potential demand for Li-ion batteries will encourage the creation of a domestic battery supply chain. In the U.S. for example, the American Recovery and Reinvestment Act (ARRA) has already offer $2.4 billion of grants for battery manufacturing facilities in order to encourage this development.

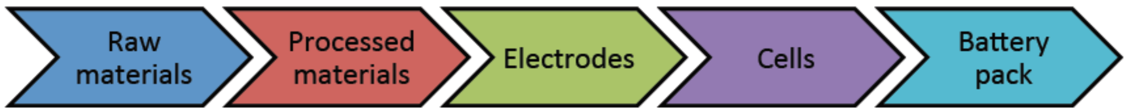


Figure 4-5. Simplified LIB manufacturing value chain

Source: Chung et al. (2015)

According to Canis (2011), p. 9, the supply chain of lithium-ion batteries includes research and development, raw material search, mining and refine, manufacturing of components, chemicals and electronics, the assembly of the batteries and electronics into cells and then into packs, marketing, financing, shipping and customer service as seen in Figure 4-5.

Following the report on lithium-ion battery supply chain by Lowe et al. (2010), p. 29, the lithium-ion supply chain can be divided into four levels: Automakers, Tier 1, Tier 2 and Tier 3 suppliers as depicted in Figure 4-6.

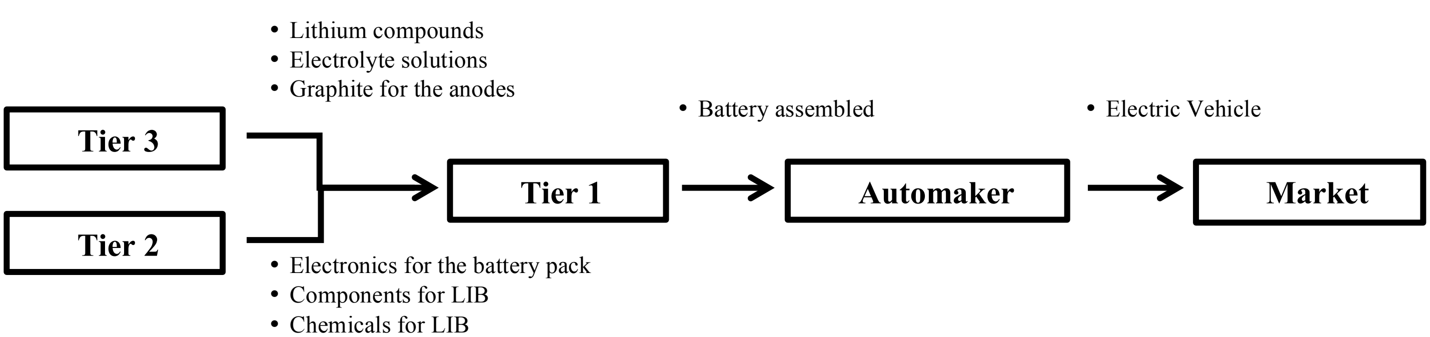


Figure 4-6. Lithium-ion battery supply chain

Tier 3 Suppliers: These suppliers often supply the Tier 1 supplier with components. Tier 3 are the suppliers in charge of lithium compounds, electrolyte solutions and graphite for the anodes. Chemtall Foote for example is a division of Rockwood Holdings that supplies over a third of all lithium used in the world.

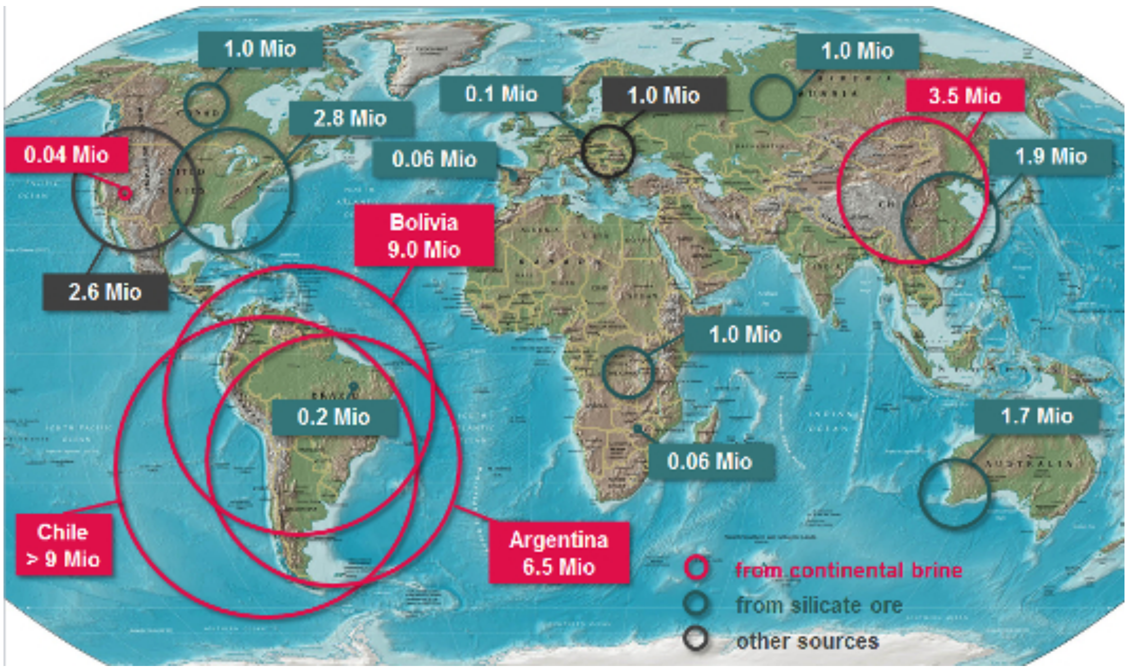


Figure 4-7. Lithium carbonate mines over the world
Source: Kohl (2015) (https://www.energyandcapital.com/articles/elon-musks-lithium-revolution/4937)

Two methods can be distinguished for lithium extraction: silicate ore and brine:

- **Brine** is water with a high concentration of lithium carbonate. The concentrations are high because lithium from rocks and sediments has already been released by the natural movements of the water. Filtering processes will be applied to extract that lithium (Khol, 2015). Brine is the major source of material for lithium carbonate because is less expensive and easier to mine it than rocks with lithium content (silicate ore). However, several places in the world such as Australia and Africa use silicate ore as the main source for extracting lithium. Figure 4-7 shows the main mines of lithium in the world according to its source of extraction.

- **Silicate ore** is lithium stored in rocks. However, lithium is found in very low concentrations. In order to extract the lithium, the rock must be mined and crushed. The mixture will be submerged in liquid to separate the lithium particles, which will be filtered before drying it back to a solid (Khol, 2015).

According to Khol (2015) the world is not short on lithium but it is on producers that can efficiently extract and refine it. The United States Geological Survey estimates that global lithium reserves amount to about 13.5 million tones while the global lithium consumption is expected to grow to 35,000 tonnes per year by 2020.

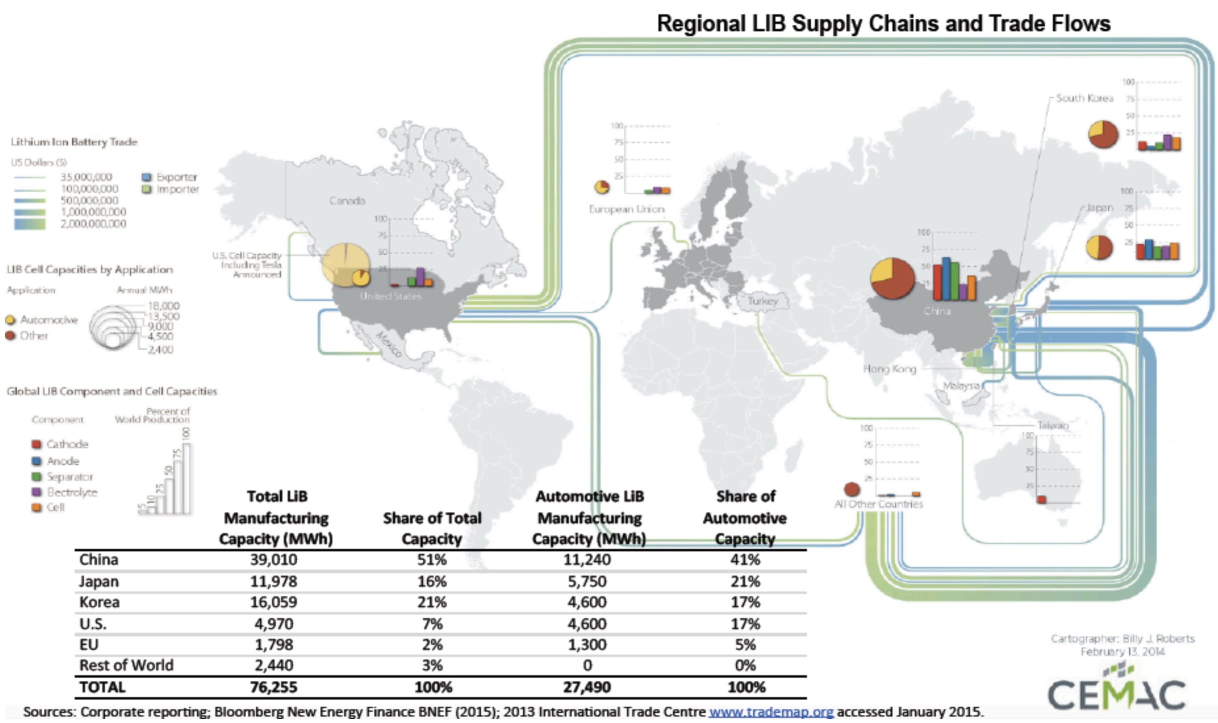
Even though China and Russia have lithium ore resources, it is cheaper for them to import this material from Chile and Argentina, the leading exporters and producers, than mine their own.

The U.S. is the world's leader consumer of lithium and has a strong foothold at this level of the supply chain, most of the raw materials come from abroad, however, in Nevada are being developed sites to supply their market.

According to Berger (2012) lithium is not going to run out in the foreseeable future, what is more, by 2020 there will be an excess in the supply that will drive down prices and undermining investments.

Aside from lithium, other materials such as manganese, nickel, cobalt, copper and aluminum are used in different forms to make LIB. Some of them are concentrated in specific locations that affect supply and pricing. More than a third of the world's production of cobalt comes from the Democratic Republic of Congo while some rae minerals for EV are mined primarily in China.

Tier 2 Suppliers: These suppliers provide the components and chemicals for lithium ion cells and the electronics for the final battery pack.



	Total LiB Manufacturing Capacity (MWh)	Share of Total Capacity	Automotive LiB Manufacturing Capacity (MWh)	Share of Automotive Capacity
China	39,010	51%	11,240	41%
Japan	11,978	16%	5,750	21%
Korea	16,059	21%	4,600	17%
U.S.	4,970	7%	4,600	17%
EU	1,798	2%	1,300	5%
Rest of World	2,440	3%	0	0%
TOTAL	76,255	100%	27,490	100%

Sources: Corporate reporting; Bloomberg New Energy Finance BNEF (2015); 2013 International Trade Centre www.trademap.org accessed January 2015.

Figure 4-8. LIB's upstream materials manufacturing

Source: Chung et al. (2015)

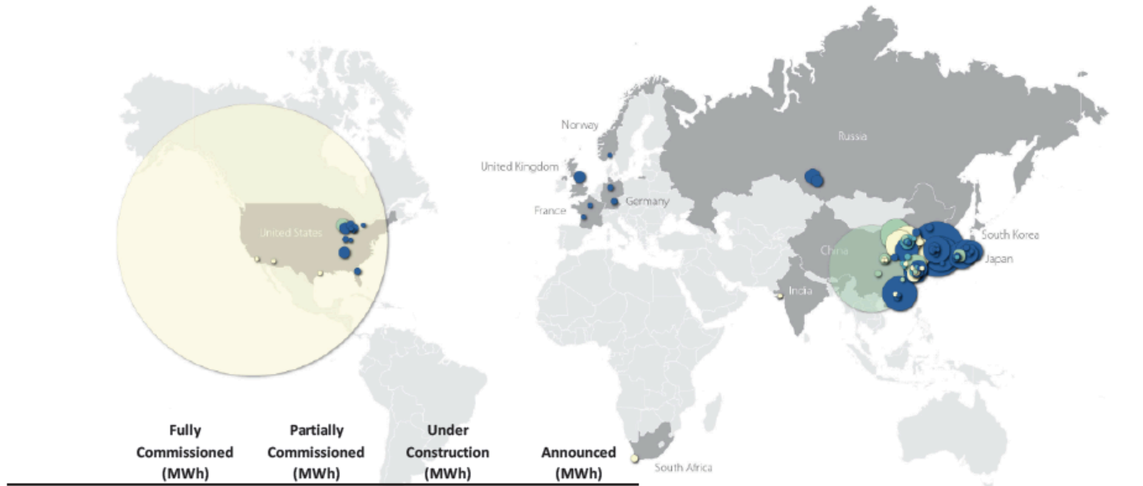
According to Figure 4-8, China Japan and Korea control the majority of automotive LIB production (79% of total production). However, the U.S. is entering into the market despite cell and battery plant operators are relatively new to the industry compared to the Asiatic countries.

Tier 1 Suppliers: These kinds of suppliers have the goal of putting all the pieces together into a battery. According to Canis (2013), this is the part of the supply chain in which the American Recovery and Reinvestment Act (ARRA) has given significant subsidies to start U.S. production. U.S. makers of LIB for EV will need to achieve high-volume production to realize economies of scale and drive unit costs down.

Referring to researchers at the Massachusetts Institute of Technology, manufacturing is the key to achieving a commercially successful EV battery. Low cost will be only achieved in large-volume and highly automated factories. Development of EVs requires R&D and manufacturing battery systems to achieve success.

Therefore, it is necessary to understand the possible economies of scale in manufacturing since manufacturing cost is decisive in the ultimate economics of EVs (An, M. I. T., 2010).

As it can be seen in Figure 4-9, LIB manufacturing capacity is primarily located in China, Japan and Korea that constitute a 85% of global fully commissioned LIB production capacity for all end-use applications. The U.S. has historically not been a leader in LIB production, however, Tesla's recent announcement of building the 35 GWh LIB manufacturing facility in Nevada will significantly increase the U.S. share.



	Fully Commissioned (MWh)	Partially Commissioned (MWh)	Under Construction (MWh)	Announced (MWh)
China	16,704	3,576	18,730	12,847
Japan	10,778	0	1,200	0
Korea	16,059	0	0	0
U.S.	3,770	0	1,200	35,000
EU	1,798	0	0	0
Rest of World	2,440	0	0	564
TOTAL	**51,549**	**3,576**	**21,130**	**48,412**

Note: This map includes factories that are fully and partially commissioned, under construction, and announced. Capacity is not disclosed for all factories.
Source: Corporate reporting. Bloomberg New Energy Finance BNEF (2015).

Figure 4-9. LIB cell manufacturing world's distribution

Source: Chung et al. (2015)

Automakers: This is the last step in the LIB supply chain in which the automakers have the role of integrating the battery into the car and then sell the EV in the market.

4.3.2 Manufacturing of Lithium-ion batteries

Regarding to Canis (2013) work about battery manufacturing for EV, LIB have generally been produced in Asia, near manufacturing sites for battery-dependent portable consumer products.

However the transition from small batteries to larger batteries designed for motor vehicles has opened the door for new entrants into the industry. Tighter tolerances on material and manufacturing specifications are required to achieve an extended cycle life, high specific energy and safety in extreme conditions that means that companies that have been successful in manufacturing LIB for consumer products may not necessarily dominate the automotive market.

When manufacturing a battery, the first thing to do is to procure the lithium, which is mined primarily in Chile. The mineral will be refined into lithium carbonate at Chilean plants and shipped as either powder or ingots to Tier 2 or 3 manufacturers. There, the lithium carbonate will be converted into lithium metal that is used in battery cells. This is a highly automated process that requires from great precision. Lithium is divided into cells heated at high temperatures for 90 minutes and tested for electrical transmission capabilities. It has been estimated that 70% of the value added in making LIB is in the development and manufacture of the cell itself, whereas the 15% is added in the assembly of the battery and 10% in the electrical and mechanical components. Cells are packaged and shipped to a Tier 1 supplier where the battery will be assembled (Rio et al., 2012).

The manufacture of large format power batteries is still in its infancy, battery manufacturing operation needs to become faster and less expensive. According to sensitive chemistry of the cells, cost and time savings cannot come at the expense of quality. That means that the solution lies in fully automating and integrating production lines. Uniform data management, engineering and communication standards ensure that all production steps are optimally coordinated (Nazri & Pistoia, 2008).

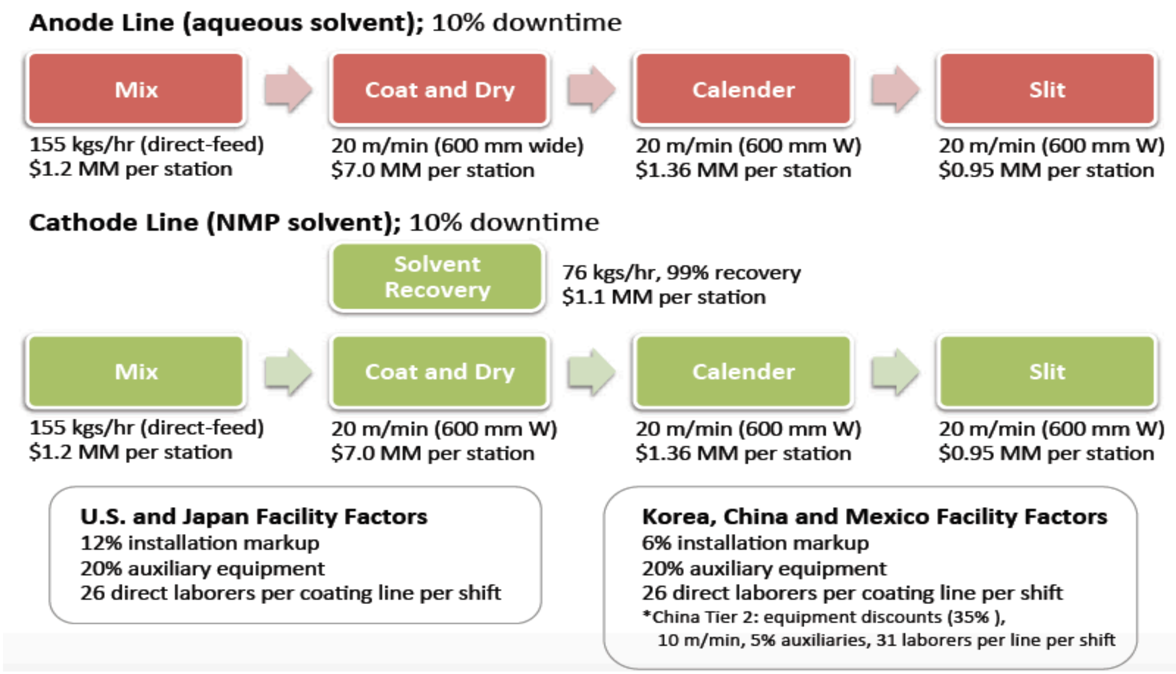


Figure 4-10. LIB cell production process (anode and cathode)

Source: Chung et al. (2015)

Leaving aside the extraction and transportation of material and final product, the manufacturing process that consumes more money and energy is the elaboration of the electrodes plus the cell assembling. According to Daniel (2008), the electrolytes are formed from pastes of active material powders, binders, solvents, and additives and are fed to coating machines to be spread on current collector foils, such as aluminum for the cathode side and copper for the anode side. Subsequent calendaring for homogeneous thickness and particle size is followed by slitting to the correct width.

According to Chung et al. (2015), The components are then stacked to separator-anode-separator cathode stacks followed by winding to prismatic cells, insertion in prismatic cases, and welding of a conducting tab. The cells are then filled with electrolyte. The electrolyte has to wet the separator, soak in, and wet the electrodes. The wetting and soaking process is the slowest step and therefore is the determining factor in the speed of the line. All other needed insulators, seals, and safety devices are then attached and connected. Then, the cells are charged the first time and tested. Often cells have to be vented during the first charge. First charging cycles follow sophisticated protocols to enhance the performance, cycling behavior, and service life of the cells. Recently, efforts have been made in combined and hybrid processing, such as direct deposition of separators onto electrodes and rapid heat treatments. Figures 4-10 and 4-11 depict the anode, cathode manufacturing process and cell assembly manufacturing process respectively, where each process is linked to its cost.

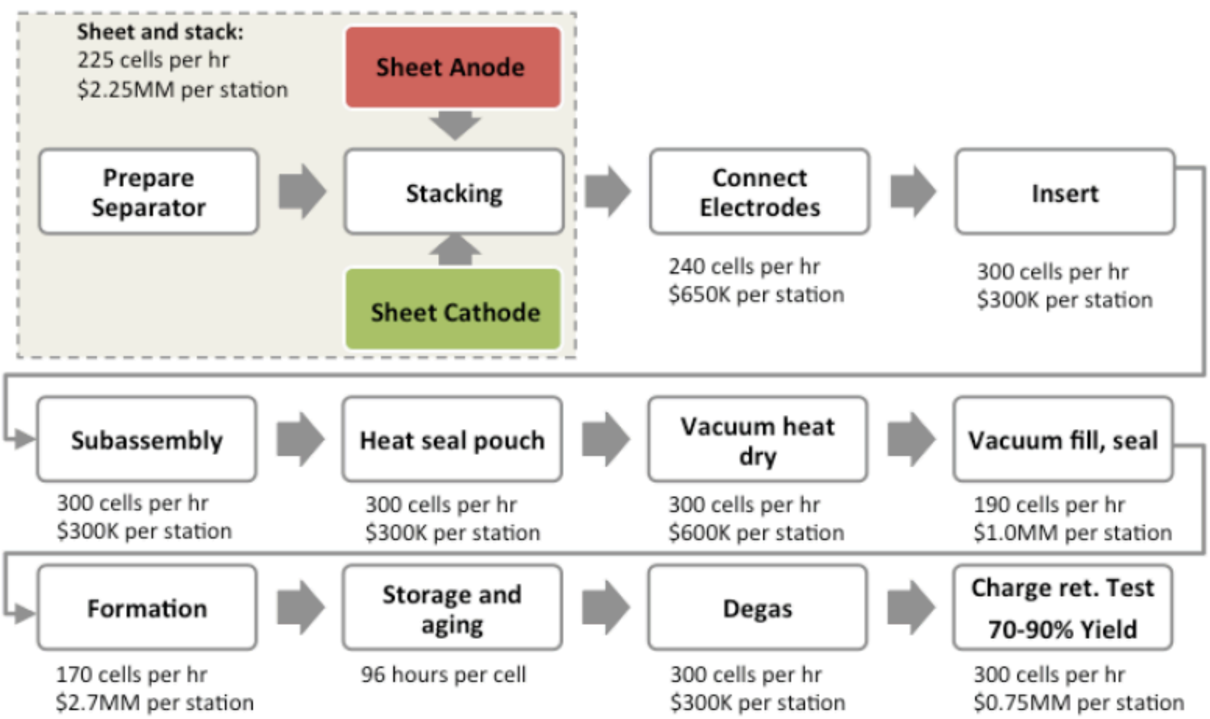


Figure 4-11. LIB cell production process (cell assembly)

Source: Chung et al. (2015)

CHAPTER 5

EFFICIENCY OF LITHIUM-ION BATTERIES

Chapter 5 introduces the concept of efficiency regarding lithium ion batteries; the chapter describes and differentiates EROI and ESOI values, focusing on batteries as energy source linked to the vehicle to grid technique. Then it is calculated the EROI value of lithium-ion batteries in different cases in order to provide conclusions about how to increase its efficiency and make these type of batteries more sustainable.

5.1 Estimation of the efficiency of Lithium-ion batteries

As it has been explained in section 2.2.1, EROI is a measurement of efficiency that compares the energy invested for producing the energy source to the energy returned from that source, which is the energy that can be used. The truth is that you have to spend energy in order to make energy (Hall, Lambert & Balogh, 2014).

Regarding storage, efficiency can be measured through two different values: the Energy Returned On Energy Invested (EROI) and the Energy Stored on Energy Invested (ESOI).

5.1.1 ESOI of Lithium-ion batteries

Batteries are the solution for providing more flexibility in managing the grid by storing renewable energy and delivering it at night or when the wind isn't blowing. Researchers have started to develop new batteries and other large-scale storage devices, nevertheless, according to Stanford University scientists, the fossil fuels and energy required to build these technologies can negate the environmental benefits of generating renewable energy (Filipowska, 2013).

As the percentage of electricity generated from renewables increases, energy storage will be required to help balance supply with demand, however, it turns out that grid storage is energetically expensive and some technologies require more energy to build and maintain than others (Shwartz, 2013).

Regarding Barnhart & Benson (2013) article published in Energy and Environmental Science, to quantify the long-term energetic costs they developed a new mathematical formula, the Energy Storage on Energy Invested (ESOI). In other words, the ***ESOI is the ratio between the amount of energy that can be stored over the life of the storage technology and the amount of energy required to build that technology***. Like EROI, the higher the ESOI value, the better the storage technology is energetically.

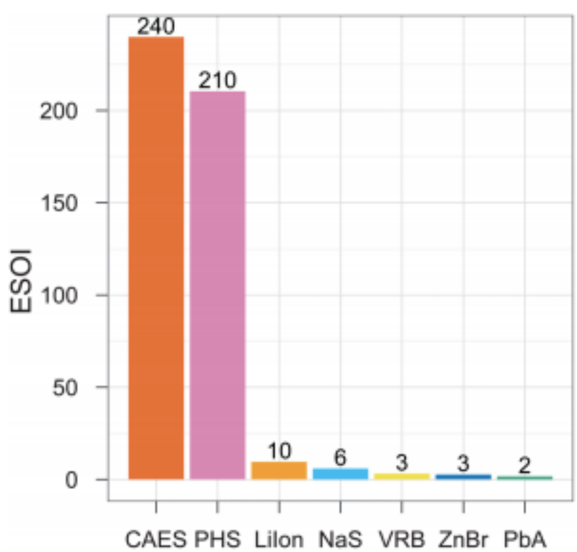


Figure 5-1. ESOI of different storage technologies (higher values are less energy intensive)

Source: Barnhart & Benson (2013)

According to Figure 5-1, all five battery types have high embodied energy costs compared with pumped hydroelectric storage (PHS) and compressed air energy storage (CAES). This is because battery technologies are made out of metals and rare metals found in specific areas in the world that require a lot of energy for being acquired and purified. On the other hand, PHS for instance, is basically a hole with a concrete dam (Shwartz, 2013).

If the ESOI is the electrical energy stored over the life of a storage technology divided by its embodied primary energy, then an ESOI value of 240 (CAES) means that it can store 240 times more energy over its lifetime than the amount of energy that was required to build it.

Regarding the ESOI value of batteries, it is clear that the less energy intensive is the Li-ion battery with an ESOI of 10 and the Lead-acid batteries are the ones considered the worst storage technology in energetic terms as they can only store twice as much energy as was needed to build it, making impractical the use of this technology for providing storage for the worldwide power grid.

Barnhart & Benson (2013) realized that an energy storage technology should last decades in order to have a high ESOI value as otherwise, the acquisition of more materials, the rebuilding of the technology and the transportation needed for replacing it would require an increase in energy cost. Therefore, the longer it lasts, the less energy will consume over time as a cost to society.

Following that idea, improving the life cycle of batteries is the solution for reducing a battery's long-term energetic costs. In other words, the ESOI value can be increased by increasing the number of times the battery can charge and discharge energy over its lifetime. While pumped hydro storage can achieve more than 25,000 cycles, that is more than 30 years of delivery clean energy on demand, lithium ion, which are the best in battery storage, only achieve 6,000 cycles. According to Shwartz (2013), increasing battery's cycle life is the most effective way for making storage technology less energy intensive.

According to Deign (2014), with the technology that we have today, it is not viable to store energy in large-scale lithium-ion batteries as it takes too much energy for building them compared to the energy that can be returned to the society. It is more efficient to curtail energy (wind energy) than build batteries to store it (Barnhart, Dale, Brandt & Benson, 2013).

5.1.2 EROI of Lithium-ion batteries - Vehicle to Grid technique

Instead of storing energy in large batteries, energy should be stored in smaller batteries through EVs and become a distributed and portable source of energy. In order to make them more sustainable and efficient, when EVs are connected to smart grids, its batteries would give back energy stored through the Vehicle to Grid (V2G) technique (Andrew, 2011).

The aim of this project then, is to analyze the batteries capability to serve both as storage and a source of energy through the vehicle to grid process (V2G). Taking that into consideration, there won't be considered the ESOI value according that this value is useful to compare between energy storage techniques. The value that will be calculated is the EROI in order that this value will let compare batteries efficiency to other energy sources. ***The EROI, then, is the ratio between the energy returned to the grid and the energy invested on the extraction of raw materials, the manufacture and the installation of the battery.***

To my knowledge, this is the first study to calculate the EROI of a battery, considering the battery a source of energy instead of a source of storage.

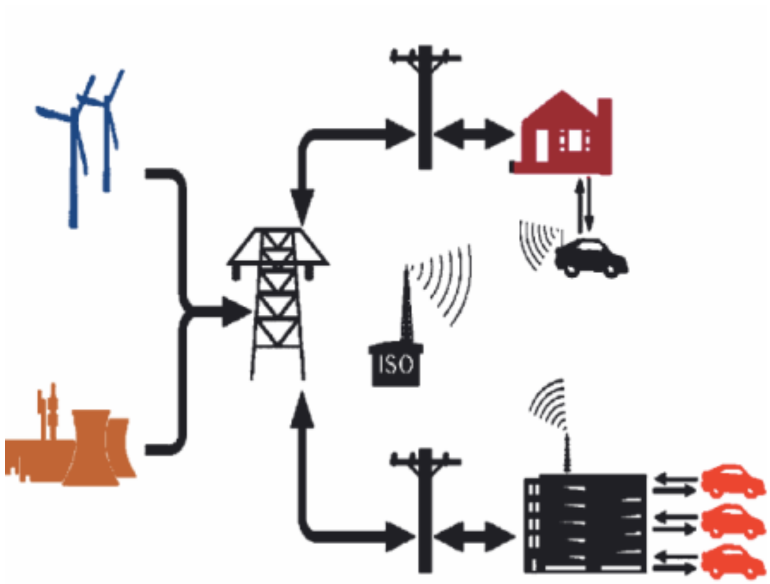


Figure 5-2. Grid layout with V2G used for energy storage

Source: University of Colorado (2008)

Figure 5-2 represents a simple scheme of the grid using the vehicle to grid technique. The well-known grid to vehicle technique (G2V) consists on using the batteries of EVs for storing extra renewable energy during off-peak hours (wind energy), extra renewable energy stored in batteries during peak hours (solar energy) or grid energy during off-peak hours, which is cheaper. However, the vehicle to grid technique (V2G), the one considered in this project, sometimes referred to as mobile-energy or smart charging, consists on giving back the energy stored in the EV's battery to the grid. According to Williams & Kurani (2006), finally EVs are capable of vehicle to grid interaction that mates an automobile with the existing electric utility system, letting vehicles be completely independent from internal combustion engines.

In order to operate in vehicle to grid configuration, vehicles must possess three elements (Tomić & Kempton, 2007):

1. Power connection to the electric grid
2. Control and communication device that allows grid operators access to the battery
3. Precision metering on the vehicle to track energy flows

Thanks to his intelligent two-way communication technique between the electric grid and the electric vehicle, utilities are able to manage electricity resources better, and it empowers vehicle owners to earn money by selling power back to the grid.

As Letendre, Denholm & Lilienthal (2006) stated, the potential benefits of a V2G transition is on the one hand, the use of electricity as a fuel which is cheaper than gasoline ($1 in electricity for a EV would travel the same distance as a gallon of gasoline for a conventional car) would imply savings on fuel purchasing. In words of the Electric Power Research Institute (EPRI), the use of EVs would save about $600 per year for the average American driver (Sanna, 2005). On the other hand, V2G configuration could provide revenue to owners by selling power back to the grid while providing assistance to transmission operators by maintaining reliability and operating standards. These electric services, known as ancillary services, would imply projected additional annual revenue between $3,777 and $4,000 per vehicle (Kempton, 2005).

Implementing the V2G concept would benefit the electric utility system by both supplying electricity to the EVs and by drawing power from them. As the infrastructure of the grid has been designed for meeting the highest expected demand of power, many utilities resources go under-utilized the majority of the time. According to Kintner-Meyer, Schneider & Pratt (2007), 84% of electrically powered cars in the U.S. could be supported by the existing infrastructure if they drew power from the grid at off-peak times according that much of the generating capacity at this period of time remains unused leading into the earning of extra revenues during these periods for the utility companies. The use of EVs as grid suppliers offers even higher benefits for utility companies. EVs can serve as distributed generators that supplement utility power plants providing valuable generation capacity at peak times aside from the ancillary services previously mentioned (Turton & Moura, 2008). These actions will balance the electrical demand curve by increasing the demand during off-peak hours that will lead into the decrease of electricity cost for customers.

The transition to this technology could reduce emissions and air pollution in the electricity sector by using the batteries in EVs as storage support for intermittent renewable energy generators, this is the electricity generated by wind turbines that generates most of the electricity at night (off-peak hours) and then inject the electricity back to the grid when required through the V2G technique. EVs would supplement large-scale pumped hydroelectric and compressed air energy storage systems (Denholm, Kulcinski & Holloway, 2005).

Regarding Sovacool & Hirsh (2009) work, the transition to V2G technology would lead into the reduction of petroleum use that would free the oil importing economies from petroleum price spikes and shocks to the global market. Consequently, national security would be enhanced and the transfer of wealth to oil producing countries would be mitigated. Not only that, but also the quality of the environment would be significantly improved repairing the damage of noxious emissions and its consequences in health, ecology and climate change. Another advantage of using this technology is the potential cost savings achieved by using electricity as a fuel instead of gasoline and improve the economic performance of electric utility companies based on renewable energy generators such as wind turbines or solar panels.

Nevertheless, there are social and technical barriers which are an impediment for V2G transition. Not only the need for huge investments is needed for building this infrastructure, but also the development of EVs is needed for the technology to succeed as they are necessary precursor and the first link in a V2G transition. Impediments relating to customer acceptance, aversion to new technologies and resistance from stakeholders of conventional vehicle infrastructure are the greatest barriers to overcome (Guille & Gross, 2009).

5.2 EROI calculation for a Lithium-ion battery used for the V2G technique

In order to calculate the EROI of a lithium ion battery, two numbers are required. On the one hand, the energy invested in the process, which is the energy embedded from extracting the raw materials to the final assembly of the battery and its transport and installation of the automakers. On the other hand, the energy returned to the society, which, in this case, is the energy injected to the grid through the vehicle to grid technique. However, different studies could have been developed by considering for example the energy returned to the society the energy injected to the grid through grid scale battery storage or also by considering the electricity used for EVs as a source of fuel instead as energy returned to the grid through V2G.

5.2.1 Energy Invested in Lithium-ion batteries

According to Table 5-1, the energy invested when building a LIB depends on the method and type of raw material used for getting the lithium. In this project, calculations will be done assuming that the method used for extracting lithium is from brines in which the energy used is significantly lower and it is the most common method used around the world.

Table 5-1. Life cycle energy values, assessment and sources for LIB materials
Source: Sullivan & Gaines (2010)

Material	PE_j (MJ/kg)	Energy Detailed[b]	Process Detailed[b]	Reference
Co-precipitation	144	Y	Y	Hittman Associates 1980
Brine → Li_2CO_3	36.6	Y	Y	Author's data
Ore → $LiOH\text{-}H_2O$	163	Y	Y	Hittman Associates 1980
Ore → LiCl	220	Y	Y	Hittman Associates 1980
Coke → Graphite	202	N	N	GREET 2.7
Pet. coke → graphite	187	Y	Y	Hittman Associates 1980

[a] Assuming U.S. grid electricity.
[b] Y = yes; N = no.

Life cycle energy values shown in Table 5-1 are function of the weight of the battery. Considering a typical EV battery with a weight of 435 pounds that is 197.3 kg, the total energy invested in the process of build a LIB from brine is 7,221.18 MJ, that can be also expressed as 2,005.9 kWh (Sullivan & Gaines, 2010). Therefore, the energy invested is **EI = 2,005.9 kWh.**

5.2.2 Energy Returned in Lithium-ion batteries

The energy returned, on the other hand is provided from the vehicle to grid technique, considering the battery as a source of energy that injects energy to the grid. This can be calculated following Equation 4.

$$ER = \delta \cdot E_B \cdot N_C \qquad \text{Equation 4}$$

Where:

- ER is the energy returned to the society, in this project, returned to the grid through V2G technique (kWh)
- E_B is the capacity of the battery (kWh/day), this is the energy provided by the battery fully charged in one cycle.
- δ is the percentage of energy in the battery that is returned to the grid through V2G technique
- N_c is the number of cycles, which is the life cycle of the battery. Assuming that 1 day = 1 cycle as the battery will be discharged every day and charged every night, the number of cycles is the lifespan of the battery (days)

However, according to Daigle & Kulkarni (2016), the life cycle of the battery is factor of the depth of discharge (DOD), that is the percentage of energy remaining in the battery. Daigle & Kulkarni (2016) state that the more the battery is used and therefore discharged, the less cycles (N_C) the battery will be able to perform and consequently, the shorter the lifespan of the battery will be. Figure 5-3 represents the relationship between the depth of discharge (%) and the number of cycles (N_c), which is the life of the battery (days) as it has been assumed that every day the battery will be discharged because of the vehicle to grid technique.

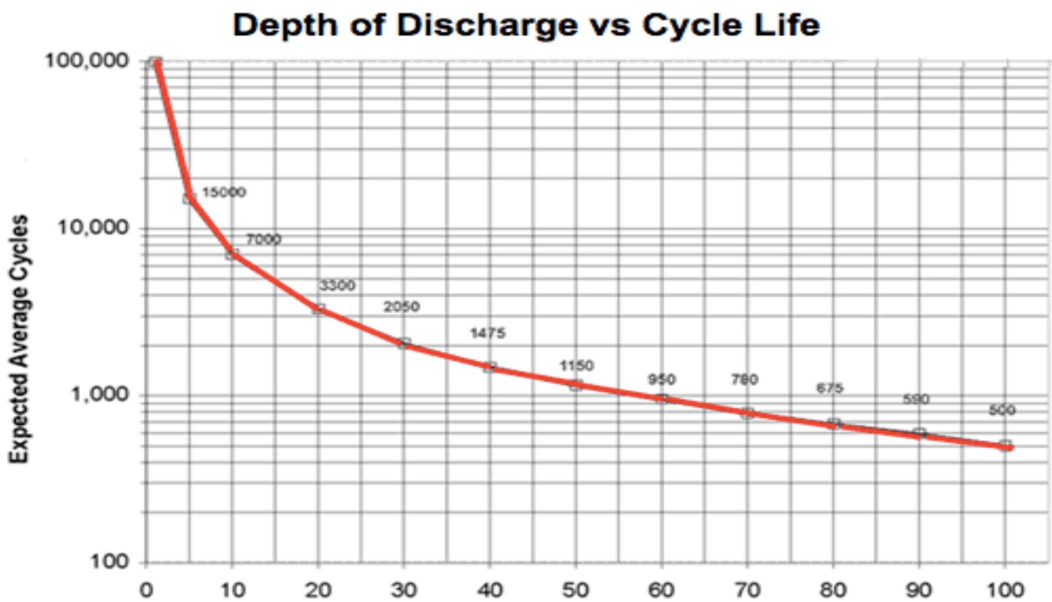


Figure 5-3. Cycle life vs DOD of LIB (20ºC)
Source: http://www.mpoweruk.com/life.htm

According to Arcus (2016), the useful life of batteries depends on the number of cycles the battery can achieve charging and discharging until the cell degrades down to 70% of its initial capacity. For lithium-ion batteries this amount of cycle is very low, 500 cycles. However, its life can be easily broadened if preventing the full charge and full discharge of the device. Thus you can do over 40,000 cycles when going from 30% discharge to 70% or 28,000 cycles if you go from 10% to 90%. In this project the life cycle of the battery has been deducted from the recommendations of Panasonic, Tesla's battery manufacturer, in which the battery should reach and provide up to a 90% of its capacity. What's more, in order to assure the right performance of the battery, the device should not be charged at its maximum. This means that the depth of discharge will reach a maximum of 90% (DOD_f) after injecting energy to the grid through V2G technique and a minimum of 10% (DOD_i) when the battery is fully charged, on other words, before traveling.

According to Shahan (2016), there is an 8 years guarantee of lithium ion batteries, however that depends on the way of usage and the temperature at which it is exposed. The available cycles, which is the life of the battery will depend on the amount of times the battery is charged and discharged (cycles consumed) and the depth of discharge reached in the battery (number of cycles reduced). According to JB Straubel, CTO of Tesla, batteries provided by Panasonic can last between 10 and 15 years minimum. However, the vehicle to grid technique that consumes a cycle per day, makes a significant reduction in the lifespan of the battery. This is the main drawback of the vehicle to grid technique; the need of reaching the maximum discharge possible of the battery in order to extract the maximum energy possible and inject it to the grid leads into the reduction of the battery life. The aim of this project is to calculate the amount of energy that should be returned to the grid according to the type of battery and the distance traveled in order to achieve the best balance between the energy returned and the life of the battery.

Cheeweewattanakoon (2014) project shows that even the battery can last these 10 years, the capacity of the battery is being affected because of time degradation, temperature and usage. While the first years you may be able to use your battery from

90% to 5%, there will be a point that the battery will only charge up to 80%. Equation 6 shows this relationship between the life of the battery and the depth of discharge.

$$ER = [E_B \cdot \left(\frac{DOD_f - DOD_i}{100}\right) - E_C] \cdot f(DOD_f) \qquad \text{Equation 5}$$

$$f(DOD_f) = 1.5238\, DOD_f^{\,2} - 272.86\, DOD_f + 13114 \qquad \text{Equation 6}$$

Where:

- DOD_i is the depth of discharge initial (%) before traveling when the battery is fully charged, according to Panasonic's recommendations this project has assumed a DOD_i = 10%

- DOD_f is the depth of discharge final (%), this is when the battery is discharged after the energy being used for traveling and injecting the energy to the grid through the vehicle to grid technique

- f (DOD_f) is the life cycle of the battery, this function links the number of cycles (N_c) to the depth of discharge final. As it has been explained in Equation 4, the number of cycles will be the number of days the battery will live.

- E_C is the energy consumed (kWh/day), this is the energy used from the battery for travelling in one cycle.

Regarding Equation 5, the energy returned to the society from a LIB depends on the capacity of the battery, the energy consumed while traveling and the depth of discharge that shows the percentage of battery daily used (δ) shown in Equation 4 and the lifespan of the battery, also known as the number of cycles (N_c).

Equation 6 is the trend/regression line of the curve depicted in Figure 5-3, it is a polynomial function that estimates the relationship between the number of cycles (N_c) and the depth of discharge after using the energy for traveling and for the vehicle to grid technique. The function selected is polynomial of 2nd order with a correlation of 0.9962 ($R^2 = 0.9962$).

Another way of expressing Equation 5 is through Equation 7 and Equation 8 that expresses the energy consumed by the vehicle through a percentage of the capacity of the battery (DOD_T), this is the depth of discharge traveled which is the depth of discharge after using the battery's energy for traveling but before applying the vehicle to grid technique.

$$ER = E_B \cdot \left[\frac{DOD_f - DOD_i - (DOD_T - DOD_i)}{100}\right] \cdot f(DOD_f) \quad \text{Equation 7}$$

$$ER = E_B \cdot \left[\frac{DOD_f - DOD_T}{100}\right] \cdot f(DOD_f) \quad \text{Equation 8}$$

Where:

- DOD_T is the depth of discharge traveled (%), this is the depth of discharge after using the battery's energy for traveling but before applying the vehicle to grid technique

Referring to Young, Wang, Wang & Strunz (2013) work, the percentage of a battery usage can be expressed both with the depth of discharge (DOD) and the state of charge (SOC). Equation 9 then, represents the relationship between the DOD and the SOC that leads into Equation 10, which is Equation 8 expressed in terms of SOC rather than in terms of DOD.

$$DOD = 1 - SOC \qquad \text{Equation 9}$$

$$ER = E_B \cdot \left[\frac{SOC_T - SOC_f}{100}\right] \cdot f(1 - SOC_f) \qquad \text{Equation 10}$$

Despite Equations 7 to 9 calculating the energy consumed by the vehicle when traveling through DOD or SOC terms, the aim of this project is to link the distance traveled to the energy returned. Following this idea, the energy consumed (E_c) can be expressed in terms of distance traveled during the day (d) and the range of the battery (R) according to Equations 11 to 13. Therefore, ***d/R is the percentage of the battery that is spent in traveling***. The difference between the depth of discharge final (customer's choice), the depth of discharge initial (10%) and the ratio d/R is the percentage of energy of the battery that will be used for being injected to the grid which multiplied by the battery capacity and the number of days this process can be done, it will be obtained the energy returned to the grid during the whole life of the battery applying the V2G technique.

$$ER = \left[E_B \cdot \left(\frac{DOD_f - DOD_i}{100}\right) - \frac{E_B}{R} \cdot d \right] \cdot f(DOD_f) \qquad \text{Equation 11}$$

$$ER = E_B \cdot \left(\frac{DOD_f - DOD_i}{100} - \frac{E_B}{R \cdot E_B} \cdot d\right) \cdot f(DOD_f) \qquad \text{Equation 12}$$

$$ER = E_B \cdot \left(\frac{DOD_f - DOD_i}{100} - \frac{d}{R}\right) \cdot f(DOD_f) \qquad \text{Equation 13}$$

Where:

- d is the total distance traveled in a day (m/day)

- R is the range of the battery in a cycle, which is a day according to the assumptions in this project (m/day)

Therefore, the energy returned to the society of a Lithium Ion battery as a source of energy for EVs linked to a V2G configuration (ER) can be calculated by knowing 4 factors: The capacity of the battery (E_B), the range of the battery (R), the distance traveled (d) and the depth of discharge final (DOD_f) assuming a constant depth of discharge initial (DOD_i) of 10%. To sum up, the energy returned is function of the battery characteristics (factors 1 and 2) and its usage (factors 3 and 4).

$$EROI = \frac{E_B \cdot \left(\frac{DOD_f - DOD_i}{100} - \frac{d}{R}\right) \cdot f(DOD_f)}{EI} \qquad \text{Equation 14}$$

In order to calculate the optimum energy returned according to the distance traveled, first it has to be calculated which is the optimum DOD_f, this will be the depth of discharge the battery will reach after the vehicle to grid performance. According to Equation 14, the EROI can be calculated for the different DOD_f according to a given capacity of battery. Figure 5-4 shows the EROI achieved depending on the DOD_f, this is the percentage the battery will be discharged. The green line depicts the maximum EROI, in other words, the DOD_f the battery should have after the vehicle to grid action in order to achieve the higher energy transferal in the whole life of the battery. The red line on the other hand, depicts the minimum EROI that a source of energy should have in order for being sustainable for the society. Following this idea, an EROI<5 implies that too much energy has to be invested in the battery creation in comparison to the energy returned to the society. Different curves have been represented according to percentage of battery consumed when traveling (d/R).

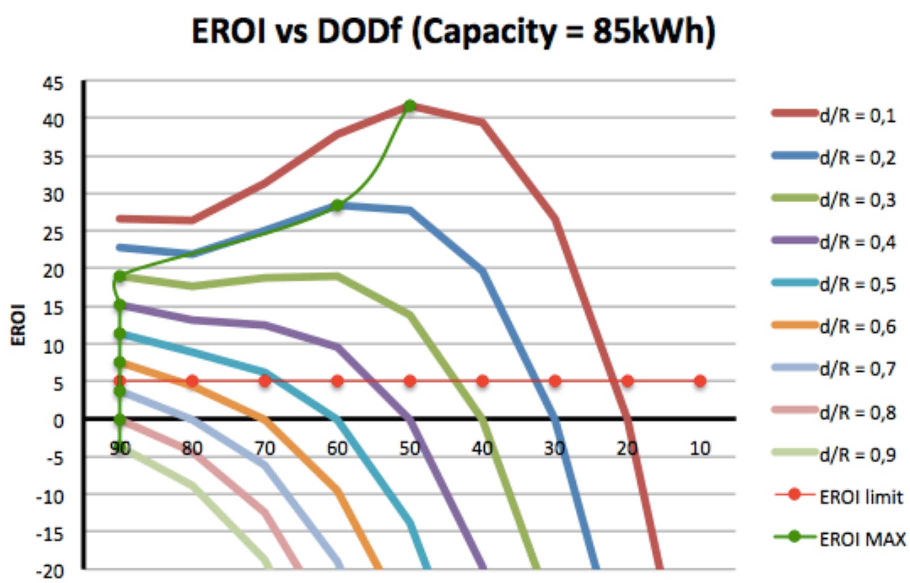


Figure 5-4. EROI vs DOD_f (Capacity = 85kWh)

What can be extracted from Figure 5-4 is ***that according to the EROI, a lithium-ion battery should not always be discharge to its maximum.*** The most efficient battery usage when performing the V2G technique in batteries of 85kWh capacity is to discharge the battery up to a 50% if the ratio d/R is 0.1, discharge the battery up to a 60% if the ratio is d/R= 0.2 and discharge the battery up to a 90% when the d/R ratio is 0.3 or higher. Knowing these numbers, Figure 5-5 can be built showing the energy that should be returned to the grid through the vehicle to grid technique. The green line represents the energy that would provide the optimum EROI whereas the red line represents the energy that would lead to the minimum EROI accepted (EROI = 5). Like in Figure 5-4, in Figure 5-5 can be seen that the optimum EROI achieved for d/R lower than 3 is not obtained by discharging the battery at its maximum rate. The best EROI for a battery of 85kWh capacity according to Figure 5-4 is achieved when the ratio d/R = 0.1 and the DOD_f = 50%. Linking these numbers to Figure 5-5, the energy that should be injected to the grid is ER = 25.5kWh/day. However, when the ratio d/R = 0.3, the energy injected to the grid should be 42.5 achieving a higher ER/day but a lower EROI according that the life of the battery will be shortened because the DOD_f would have increased.

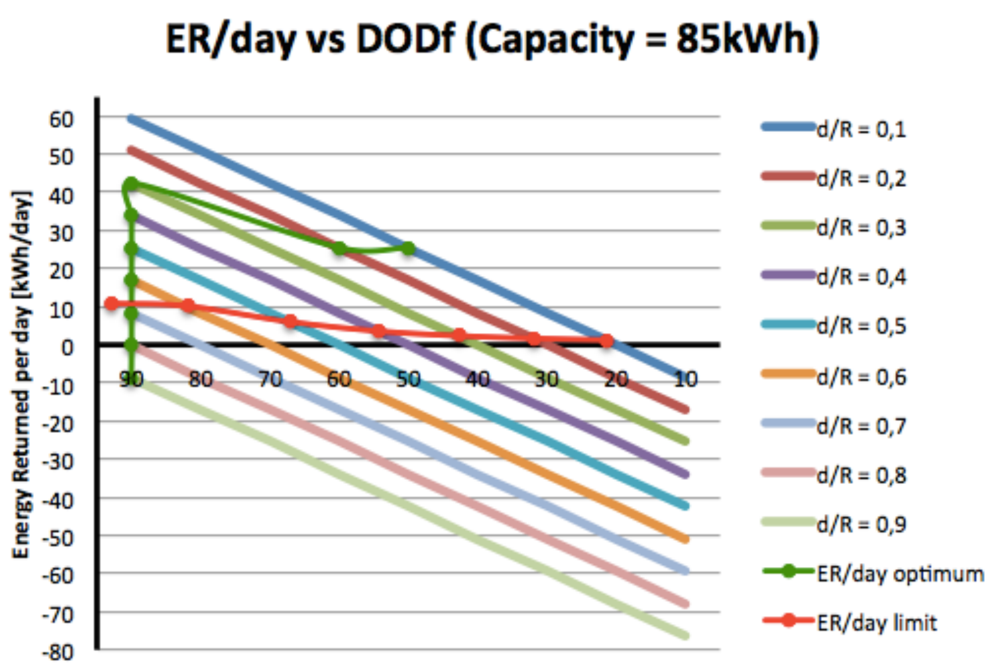


Figure 5-5. ER/day vs DOD_f (Capacity = 85kWh)

More graphics can be elaborated by changing the capacity value of the battery. Figures 5-6, 5-8 and 5-10 depict the EROI for different values of DOD_f and compared to different d/R values according to a battery capacity of 60kWh, 40kWh and 30kWh respectively. On the other hand, Figures 5-7, 5-9 and 5-11 represent the daily energy returned for different values of DOD_f and compared to different d/R values according to a battery capacity of 60kWh, 40kWh and 30kWh respectively. These values of battery capacity selected are the most used in the EV market.

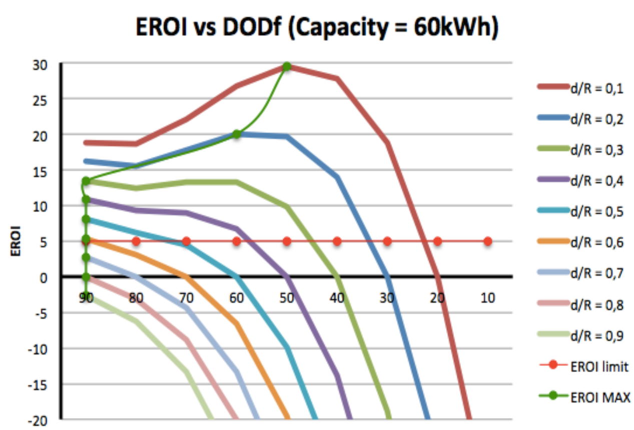


Figure 5-6. EROI vs DOD_f

(Capacity = 60kWh)

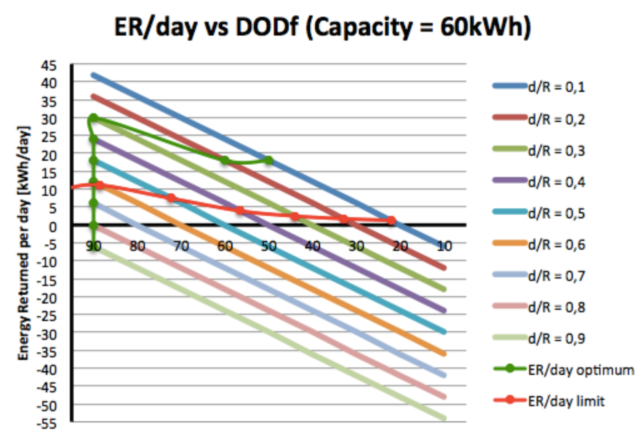


Figure 5-7. ER/day vs DOD_f

(Capacity = 60kWh)

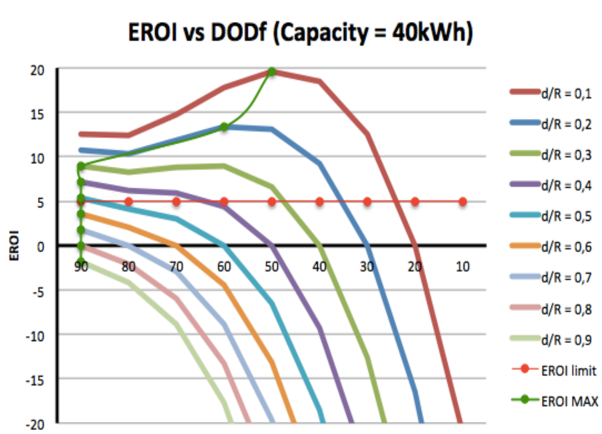


Figure 5-8. EROI vs DOD_f

(Capacity = 40kWh)

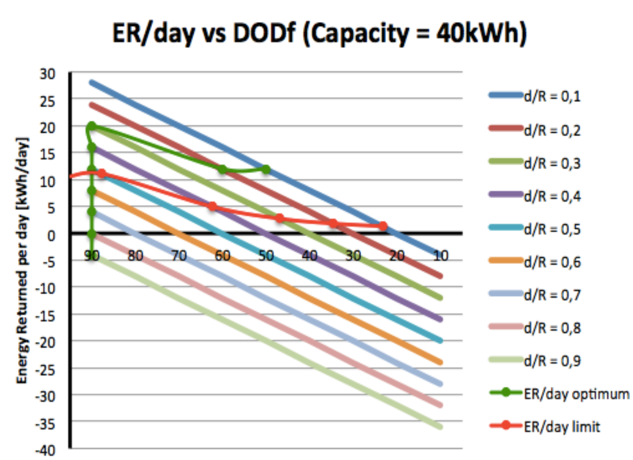


Figure 5-9. ER/day vs DOD_f

(Capacity = 40kWh)

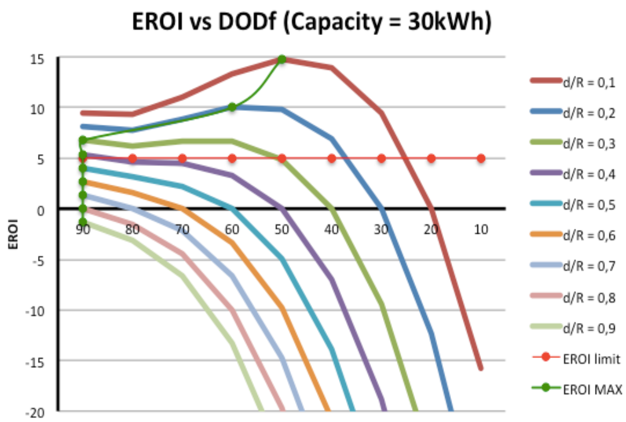


Figure 5-10. EROI vs DOD_f

(Capacity = 30kWh)

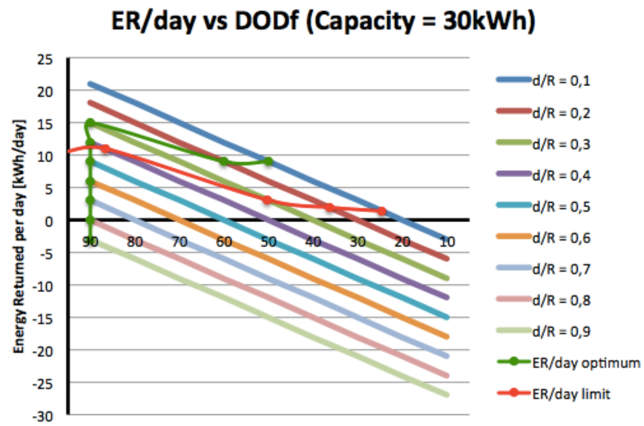


Figure 5-11. ER/day vs DOD_f

(Capacity = 30kWh)

As the ratio d/R remains constant between all the Figures from 5-4 to 5-11, the optimum EROI for the different capacities will be found at the same DOD_f, however, as it can be seen in Figure 5-12, the value of the optimum EROI will fluctuate according that the higher the capacity, the more energy can be returned to the grid. In other words, 50% depth of discharge of an 85kWh battery is a higher amount of energy than a 50% depth of discharge of a 30kWh battery.

Figure 5-12 then, represents the optimum EROI obtained with the optimum DOD_f (found in Figures 5-4, 5-6, 5-8 and 5-10) for the different values of d/R according to the capacity values already mentioned. Figure 5-13 on the other hand, shows the energy returned to the grid for different d/R values and according to different battery capacities. As in Figure 5-12, Figure 5-13 curves have the same shape for the different capacity values because the value d/R remains constant, leaving the capacity the only variable of the equation.

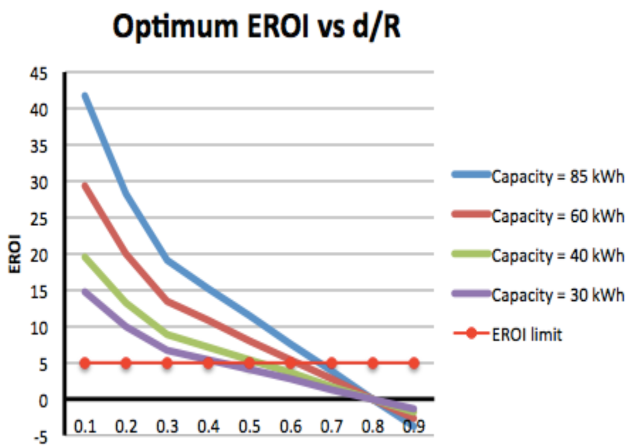


Figure 5-12. EROI vs d/R

(Optimum DOD_f for each d/R)

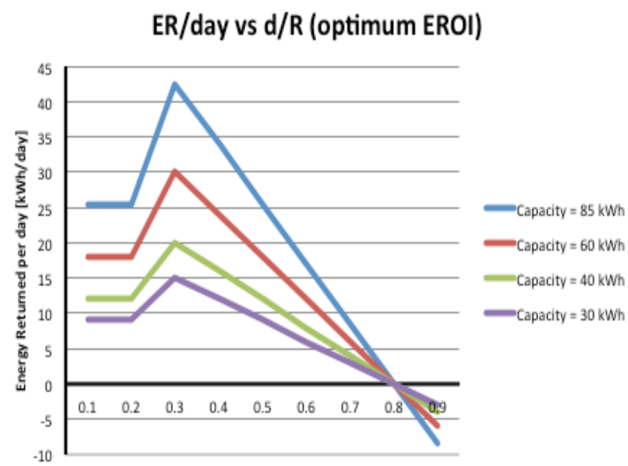


Figure 5-13. ER/day vs d/R

(Optimum DOD_f for each d/R)

5.2.2.1 Optimum Energy Returned in Lithium-ion batteries: EV market analysis

Focusing on the EV market, a more detailed study can be done. Using real data shown in Table 5-2, more accurate results can be provided for energy returned in lithium-ion batteries.

Table 5-2 shows the EVs with higher revenues in the market of 2017 with LIB (Young et al., 2013). Table 5-2 shows not only the company, country or vehicle model but also the capacity of its battery and the range, values that depends on the battery type (factors 1, 2).

The remaining factors that are related to the usage, are the distance traveled which will be a variable and the DOD_f which will be calculated in order to achieve the higher EROI leading into the optimum amount of energy that should be returned to the grid through the V2G technique.

Table 5-2. LIB characteristics for EV found in the market 2017
Source: Young et al. (2013)

Company	Country	Vehicle Model	Capacity	Range
Tesla	USA	Model S	85 kWh	400 km/cycle
BYD	China	E6	82 kWh	400 km/cycle
GM	USA	Chevrolet Bolt EV	60 kWh	383 km/cycle
Renault	France	Zoe	41 kWh	400 km/cycle
Toyota	Japan	Rav4 EV	42 kWh	165.8 km/cycle
Volkswagen	Germany	E-golf	35.8 kWh	200 km/cycle
Ford	USA	Focus Electric	33.5 kWh	160.9 km/cycle
BMW	Germany	I3	30 kWh	175.5 km/cycle
Nissan	Japan	Leaf EV	30 kWh	172.2 km/cycle

Regarding Table 5-2, the EVs selected have capacities that range from 30kWh, 40kWh, 60kWh and 85kWh which are the ones studied in Figures 5-4 to 5-13. Following this idea, Figure 5-14 compares the optimum EROI (optimum DOD_f for each distance) for the different EVs battery capacities keeping the value d/R constant. While keeping the ratio d/R constant among the different EVS models, this shape of the curve will be the same as the optimum EROI will be achieved with the same value of DOD_f for. What can be deducted from Figure 5-14 is that the higher the capacity, the higher the EROI will be, highlighting that the lower the d/R ratio, this is the distance traveled vs the range of the batter, the higher the EROI will be as more energy will be available for being sent back to the grid.

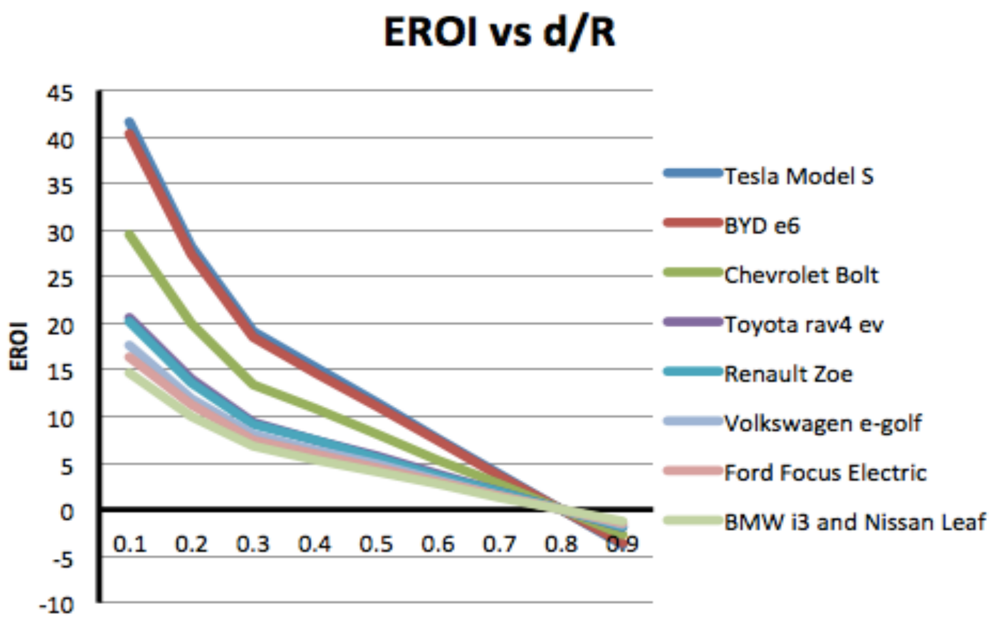


Figure 5-14. EROI vs d/R for different EVs models (Optimum EROI for each d/R)

Figures 5-15 to 5-23 go a step further and also take into account the range of the battery (R) meaning that the distance will also be calculated. Figures 5-15 to 5-23 study the EROI for the different battery characteristics (capacity and range) of the EV presented for a range of distances given. For each EV model has been calculated the distance that according to its battery range would make the ratio d/R equal to 0.1, 0.2 and so until 0.9. This will help compare the distance that should be traveled with each vehicle by spending the same percentage of the battery capacity. As the ratio d/R will remain constant for all the models, the optimum DOD_f for achieving the optimum EROI will be the same for all the models.

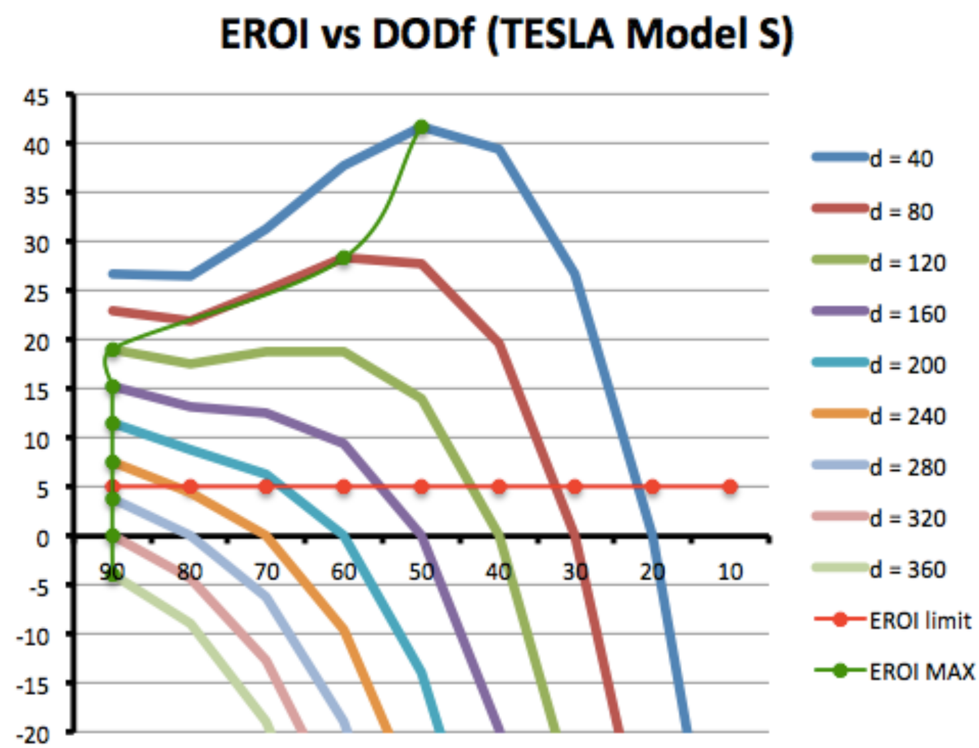


Figure 5-15. EROI vs DOD_f (Tesla Model S)

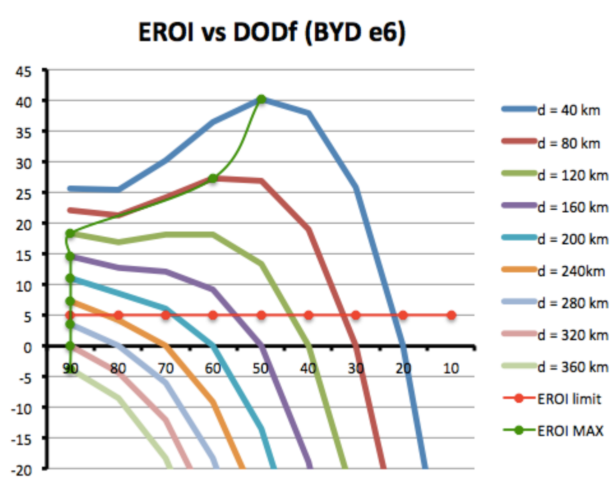


Figure 5-16. EROI vs DOD_f

(BYD E6)

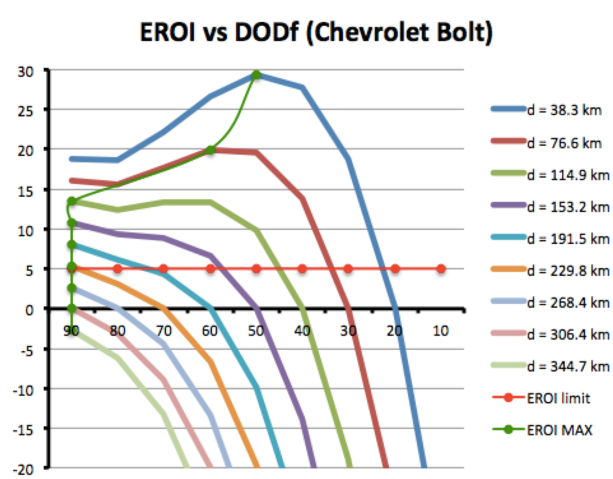


Figure 5-17. EROI vs DOD_f

(Chevrolet Bolt)

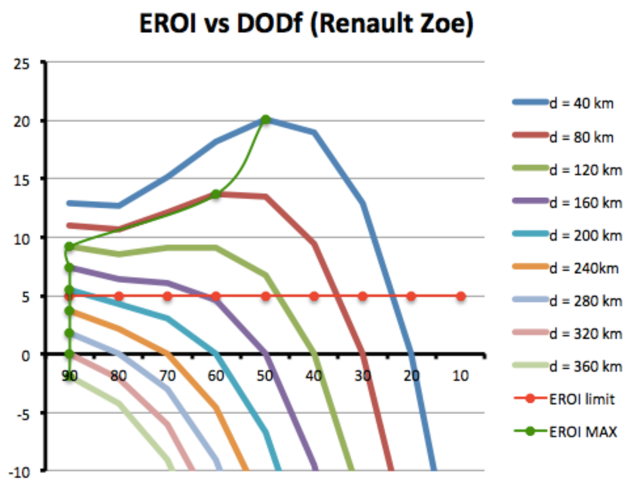


Figure 5-18. EROI vs DOD$_f$

(Renault Zoe)

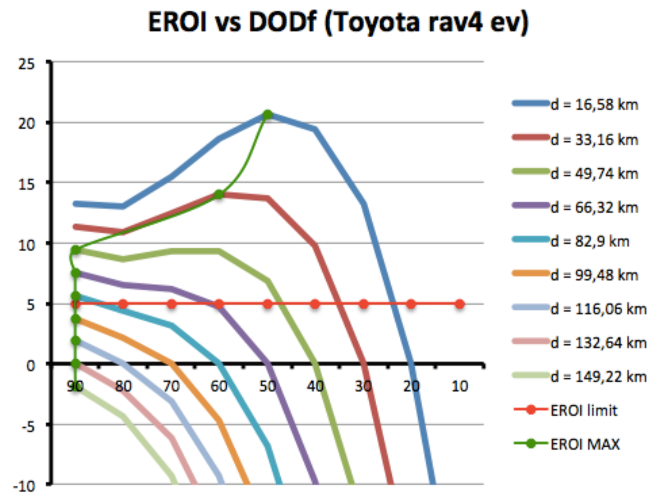


Figure 5-19. EROI vs DOD$_f$

(Toyota rev4 EV)

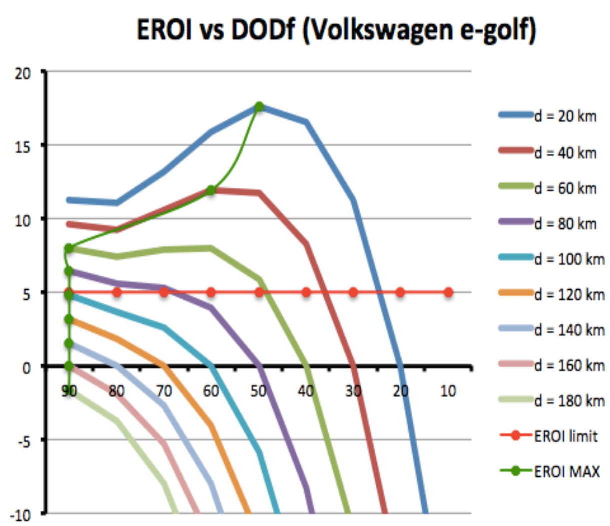


Figure 5-20. EROI vs DOD$_f$

(Volkswagen e-golf)

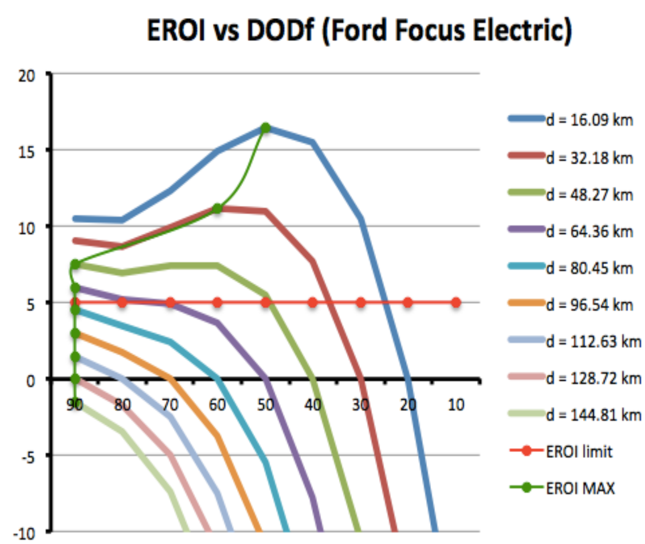


Figure 5-21. EROI vs DOD$_f$

(Ford Focus Electric)

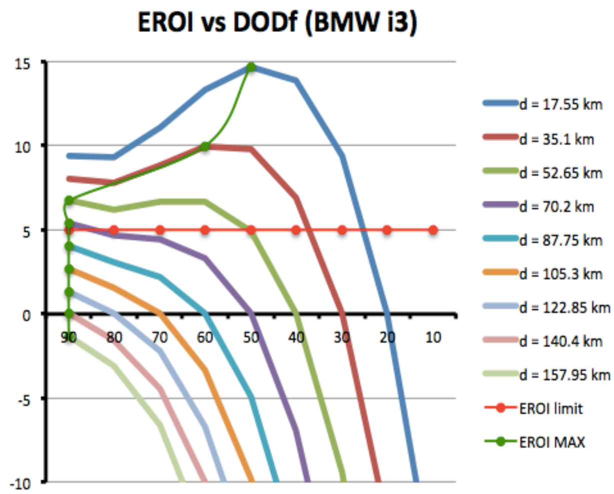


Figure 5-22. EROI vs DOD_f

(BMW i3)

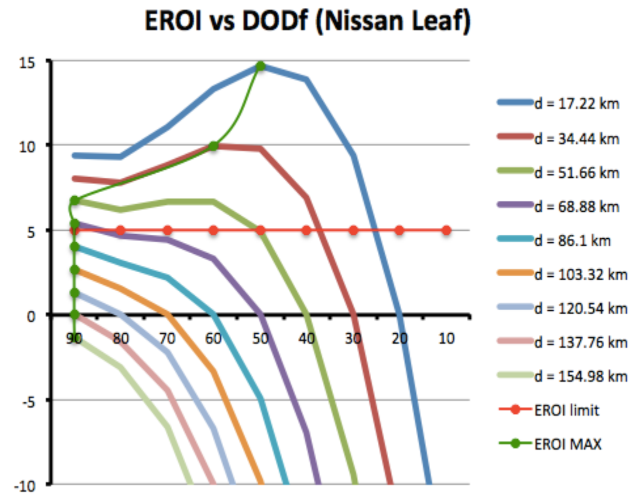


Figure 5-23. EROI vs DOD_f

(Nissan Leaf)

The aim of the project though, is to calculate the amount of energy that should be return to the grid through the vehicle to grid technique in order to achieve the maximum EROI of the LIB battery. This amount of energy has to take into account the life of the battery because the more energy is injected to the grid, the higher the DOD_f and therefore the shorter the lifespan will be.

Consequently, the energy returned value will depend mainly on the distance traveled, this is the energy consumed that will be different for every battery type. Larger capacity and battery range will have higher EROIs for equal distances. Figures 5-24 to 5-28 represent the EROI obtained at different DOD_f for a given distance and comparing the different EVs found in the market. The distances chosen are 20km, 80km, 100km, 120km and 46.99km, which is the average distance traveled by Americans every day (Waldron, 2015).

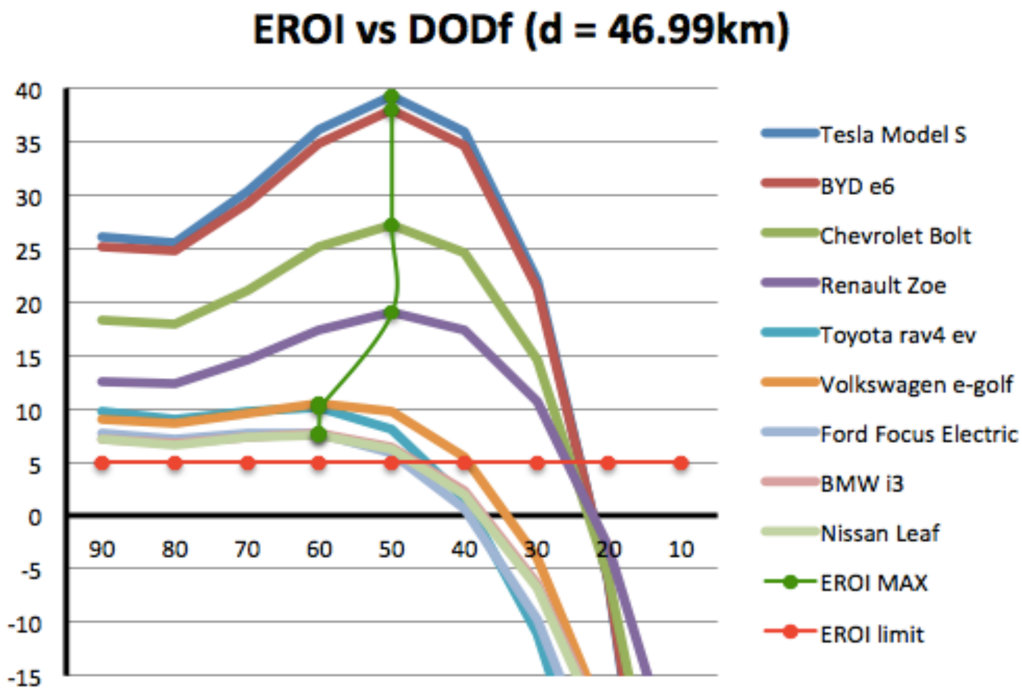


Figure 5-24. EROI vs DOD_f (d = 46.99km)

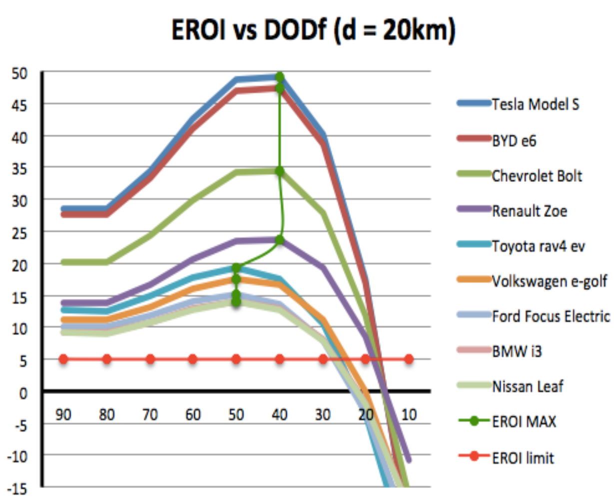


Figure 5-25. EROI vs DOD_f

(d = 20km)

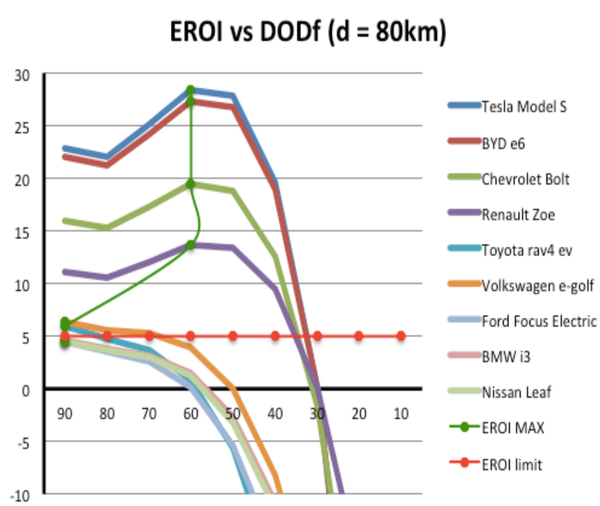


Figure 5-26. EROI vs DOD_f

(d = 80km)

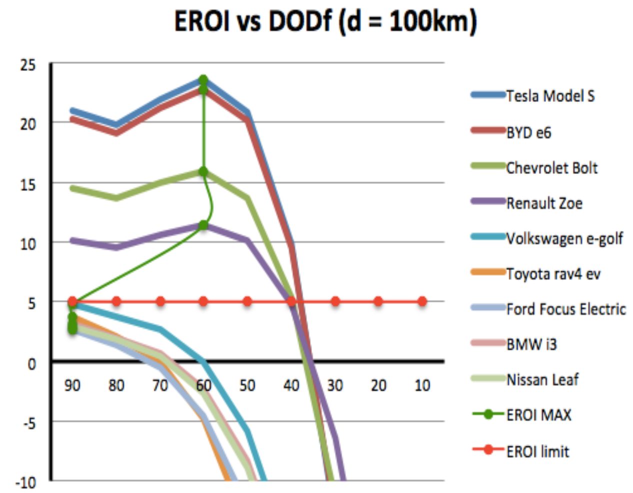


Figure 5-27. EROI vs DOD_f

(d = 100km)

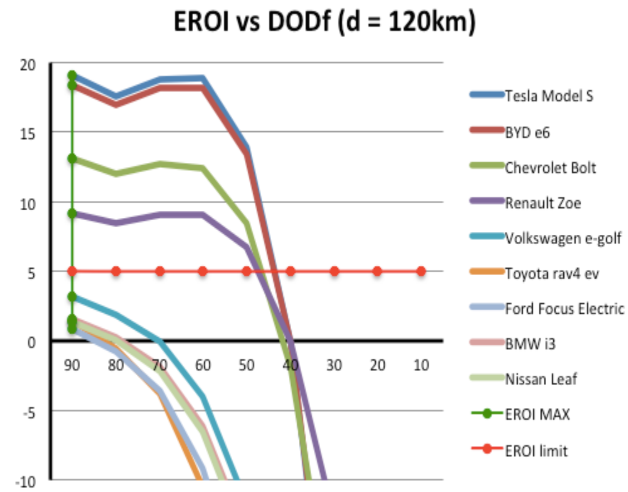


Figure 5-28. EROI vs DOD_f

(d = 120km)

The green line depicted in Figures 5-24 to 5-28 represent the maximum EROI, showing the optimum DOD_f that should be achieved after injecting energy to the grid through the vehicle to grid technique. By reaching this DOD_f, the balance between the battery lifespan and the energy returned will be optimized in order to achieve the maximum EROI. In Figure 5-17 can be seen that for Tesla, BYD, Chevrolet and Renault the DOD_f desired should be 50% while in the rest of the EVs shown, the DOD_f should be 60%. According to Figures 5-24 to 5-28, the lower the distance traveled, the less percentage of battery consumed by traveling meaning that the optimum EROI is achieved by discharging less the battery. On the other hand, for higher distances, the optimum EROI is achieved discharging more the battery reaching the maximum discharge (DOD_f) at 120km for all the vehicles. This model then succeeds in finding the optimum DOD_f for the vehicle used and the distance traveled. The red line depicts the EROI limit, this is the point from which is worth it injecting energy to the grid, in other words, the least value of DOD_f accepted after applying the V2G technique meaning the process will be considered sustainable. The EROI limit then is useful for knowing which type of vehicle is sustainable for using the vehicle to grid technique according to a specific distance.

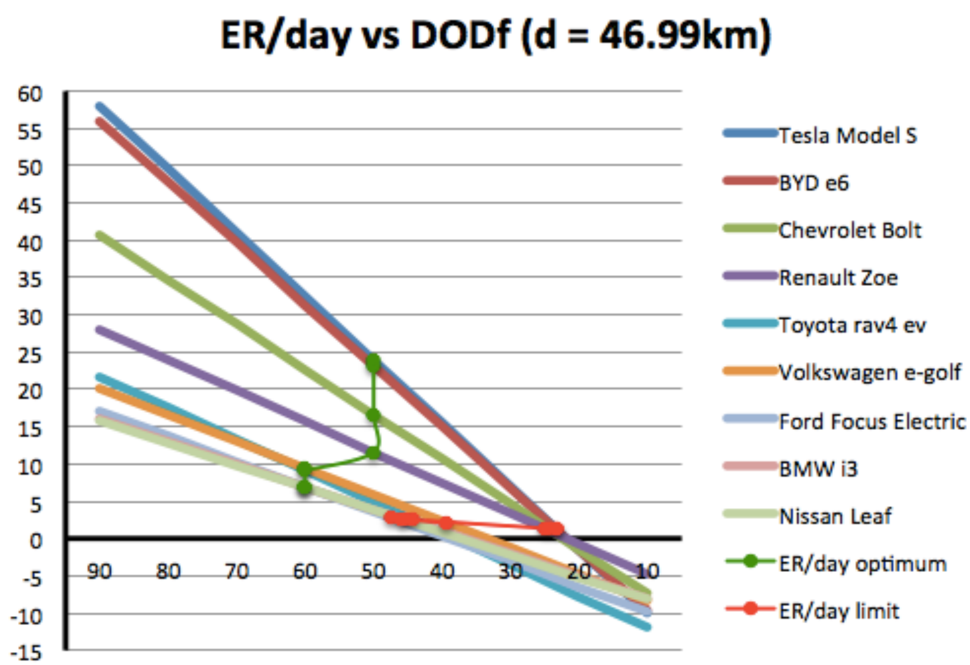


Figure 5-29. ER/day vs DOD_f (d = 46.99km)

Figure 5-29 represents the energy returned to the grid according to different DOD_f values for a distance of 46.99km which is the average distance traveled daily by Americans (Waldron, 2015). Figure 5-29 also compares these values to the EVs found in the market showing again that the ones with higher capacity and battery range are able to inject more energy to the grid. However, as it has been studied in Figures 5-4 to 5-11, the optimum energy returned (green line) is the one that matches the optimum EROI obtained with the optimum DOD_f in order to balance the energy returned and the lifespan of the battery, that is the number of cycles. Each vehicle also have a limit energy returned value depicted by the red line that links the energy returned to the EROI = 5 showing the DOD_f limit for each model and the minimum energy that should be returned to the grid.

Figure 5-30 and 5-31 show the case study of a specific EV, the Tesla Model S. This vehicle has a battery capacity of 85kWh and a battery range of 400km/cycle. Figure 5-30 and 5-31 depict the EROI according to the different DOD_f options and compares it with a wide range of distances traveled which are around the average distance already mentioned.

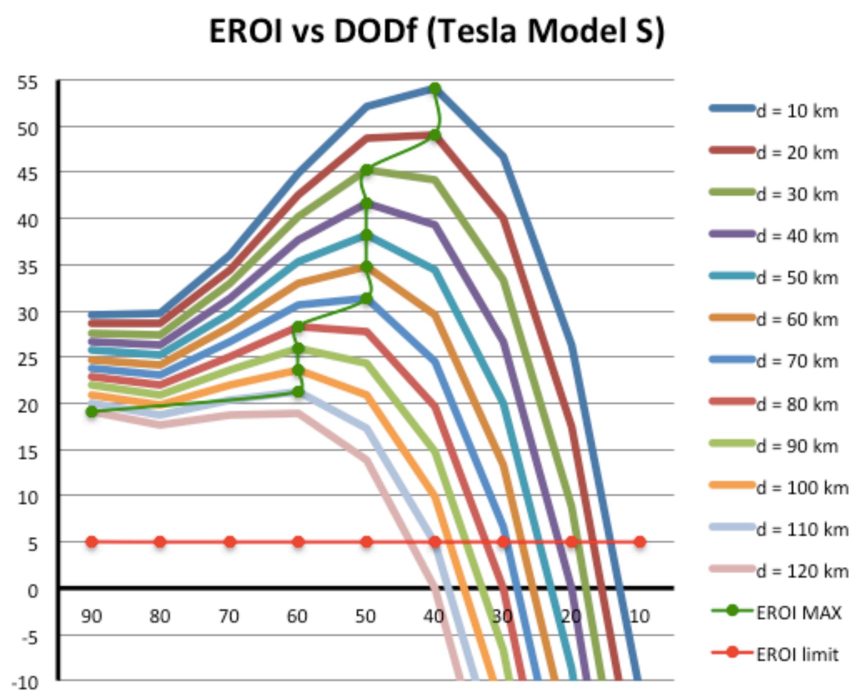


Figure 5-30. EROI vs DOD_f (Tesla Model S)

In the case of Figure 5-30, it can be clearly understood the different DOD_f that should have the battery after the V2G technique, after injecting energy to the grid. Green line then links the optimum EROI to the optimum DOD_f showing that the DOD_f increases as the distance traveled is higher, this is the energy consumed while traveling increases.

To sum up, when using the Tesla Model S for distances lower than 20km a day, the DOD_f should be a 40%, when traveling distances from 30km to 70km per day, the battery should be discharged a 50%, if the distance traveled is between 80km and 110km, the optimum DOD_f is 60% and for distances of 120km or above the value of DOD_f should be 90% which is the maximum allowed according to Panasonic.

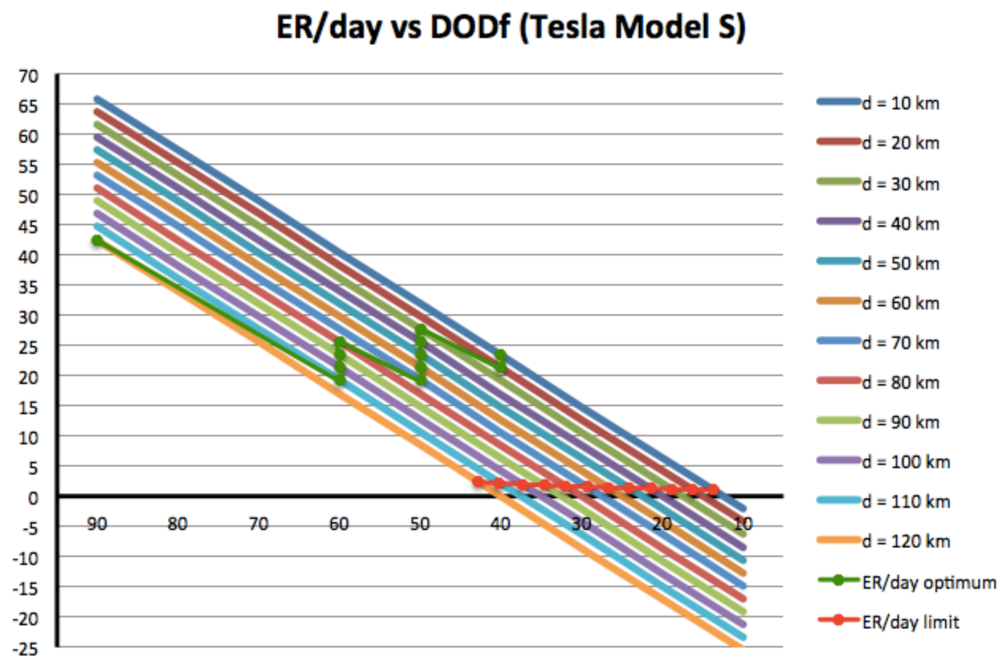


Figure 5-31. ER/day vs DOD_f (Tesla Model S)

Regarding Figure 5-31, this is the key of how to use the Tesla Model S battery when performing the vehicle to grid technique in order to reach the greatest amount of energy returned during its life, achieving the maximum value of EROI and therefore being more sustainable and earning the greatest amount of money by selling energy to the grid. The green line represents the optimum number of energy that should be returned to the grid through the V2G technique according to the values of DOD_f obtained in Figure 5-30 linked to the optimum EROI. Figure 5-31 compares these numbers for a wide range of distances that are the most typical to drive in a day according to the American's daily distance average traveled.

Gathering all the data provided in Figures 5-4 to 5-31, it can be verified that for specific battery characteristics (range and capacity) and for specific conditions of usage (distance and DOD_f) the EROI is pretty high, making the process of vehicle to grid technique for LIB batteries and efficient and sustainable source of energy for society. Considering the Tesla Model S, one of the vehicles with best benefits related to its battery with a range of 400 km and a capacity of 85 kWh and assuming a total distance traveled of 80 km/day (ratio d/R = 0.2). If the battery has a total DOD_f after the vehicle to grid technique of 60% meaning that the SOC_f is 40% (higher EROI according to Figure 5-30), and the DOD_i before traveling is 10%, meaning that the SOC_i is 90%, guaranteeing the safety standards for preventing battery damage, the energy returned would be of 25.5 kWh/day, assuming that every day the distance traveled remains constant, the energy returned during the whole life of the battery will be 56,816.04 kWh. Calculating the EROI, ratio of the ER and EI, this means an EROI of 28.32, which proves to be higher than wind (EROI = 18) and solar (EROI = 6.8).

CHAPTER 6

STRATEGIC APROACHES TO V2G – EROI OPTIMIZATION

Chapter 6 shows the different strategies that can be applied for optimizing the EROI value of lithium-ion batteries for electric vehicles with a vehicle to grid configuration through both increasing the energy returned and decreasing the energy invested. The chapter also discusses the impact of applying those strategies in both social and economic level.

6.1 Strategies for increasing the EROI of lithium-ion batteries for EVs

The aim of this project is to also study new strategies for improving the EROI in order to make the lithium ion batteries an efficient and sustainable source of energy for the future.

Regarding Equation 3, there are two ways of improving the EROI:

- Increasing the Energy Returned (ER)
- Decreasing the Energy Invested (EI)

6.1.1 Strategies for increasing the Energy Returned

As it has been studied along section 5.2.2, the ER of lithium ion batteries as a source of energy based on vehicle to grid configuration, depends on the battery characteristics (battery capacity and battery range) and the battery usage (daily distance travelled and the final depth of discharge of the battery (DOD_f), this is related to the amount of energy injected to the grid and the lifespan of the battery).

To sum up, in order to improve the EROI through increasing the energy returned to the society, improvements have to be applied over these 4 factors.

6.1.1.1 Strategies for increasing the Energy Returned through technology

In order to improve the two factors related to the battery characteristics, improvement in technology and breakthroughs are a requirement. More powerful batteries with larger capacity and a wider battery range would let the injection of more energy to the grid or the conservation of this energy in order to extend its cycle life as more energy will be remaining after travelling same distances. According to Figures 5-12 and 5-13, the higher the capacity, the higher the EROI.

Regarding the range, by comparing the Renault Zoe and the Toyota Rav4 EV, vehicles with a similar capacity 41kWh and 42kWh respectively, but a completely different range of 400km/cycle and 165.8km/cycle respectively, it can be deducted that the EROIs are completely different. According to Figures 5-24 to 5-28, for equal distances travelled, the EROI of the Renault Zoe is higher than the Toyota because the energy consumed when travelling will be lower and therefore, more energy will be available for being injected to the grid or conserved so as to have more cycles, which is lifespan.

In order to improve both the range and capacity, breakthroughs have to focus on improving the chemistry and material of the battery. EV battery research should focus on improving storage (energy density) and power capacity (power density); this is by developing higher voltage batteries that can be achieved through research in the electrolyte. According to Lee (2016), at the material level, these batteries require materials that support high power and a wide state of charge range as well as minimal impedance growth and calendar aging. Regarding cell level, it is required new chemistry and electrode designs achieving shorter and thicker electrodes reducing the overall electrode area and therefore minimizing the battery size and cost.

6.1.1.2 Strategies for increasing the Energy Returned through efficient usage

If focusing on improving the factors related to the battery usage, conclusions extracted from Figures 5-4 to 5-31 have to be applied. This is by discharging the battery the optimum percentage in order to achieve the higher EROI (Equation 14) that leads into injecting the calculated amount of energy to the grid that matches the higher EROI and the optimum DOD_f (Equation 13). Therefore, the depth of discharge final (DOD_f) will be the percentage of energy of the battery's capacity that should be remaining in the battery in order to balance the energy returned to the grid and the cycle life of the battery so as to achieve the higher EROI during its life. The distance factor, is something that cannot be changed as this factors depends on every single customer of the EV, however, Figures 5-24 to 5-28 provide a good analysis about which specific model of electric vehicle should be selected according to its distance in order to achieve a worthy EROI. Nevertheless, no matter the distance traveled, the optimum EROI will be always achieved by the vehicle with the best combination of capacity and range.

The main drawback of the vehicle to grid (V2G) technique is that the process of charging and discharging every day the battery damages the useful life of the battery, meaning that there will be less number of cycles (N_c) available leading into a reduction of the EROI. That is why, the solution is to use and discharge wisely the battery in order to balance the energy returned and the lifespan of the battery. Following this idea, graphene is said to be the future in the battery field as this material can provide three times the energy capacity and reduces 100 times the charging time. This means that a vehicle with a 400km range would be 1000km range and that the amount of cycles, its lifespan would be doubled increasing significantly its EROI (Wang et al., 2011).

6.1.2 Strategies for decreasing the Energy Invested

This second action, unlike the increase of the energy returned solution, is focused on reducing the energy used for building the battery itself. The factors to take into account in this case are: the weight of the battery and the supply chain.

According to the Sullivan & Gaines (2010), the energy invested depends on the weight of the battery, therefore the more powerful the battery is, the bigger and the heavier it will be. In this project, it has been assumed the same weight for all EVs implying that the energy invested won’t vary between models. In order to decrease the battery weight, new technology and breakthroughs are required; this is the development of a new material and chemistries such as batteries that uses air for making them lighters.

Regarding improvements in the supply chain, several solutions are found and can lead into a reduction of cost and energy invested when building a lithium ion battery.

One of the factors that encourages the creation of a domestic supply chain is the automobile plants practice just-in-time manufacturing, in which the suppliers are located near the assembly plants. The advantage for automakers and the whole supply chain system of having the lithium-ion battery suppliers near their assembly plants is that makes the process more cost-effective as assembling batteries near the motor vehicle prevents the transportation of the heavy weight of large lithium-ion batteries from thousands of miles away (Zackrisson, Avellán & Orlenius, 2010).

When focusing on improving the supply chain, according to section 2.3, the key remains in solving the problems of the processes that require higher energy and therefore are easier to improve. When making a lithium-ion battery, 70% of the value added in making lithium-ion batteries is in making the cells, 15% in battery assembly and 10% in electrical and mechanical components. Therefore, the making of the cells is the process where all the efforts should be focused on. Identifying and adopting advanced processing technologies in order to increase coater speed and other unit operations can be one of the solutions in the manufacturing level (Chung et al., 2015).

Supply chain developments, access to materials and production expertise are not the only factors that would drive costs down and improve the EROI. The increase of supply chain competition and the increase in battery production could also drive batteries costs down because of economies of scale (Wang, Gaustad, Babbitt & Richa, 2014).

Last but not least, recycling is a great solution concerning the improvement of the EROI in lithium-ion batteries. According to Hendrickson et al. (2015), recycling lithium is the solution not only for reducing costs but also for not to worry about the extinction of that element. With the current usage of lithium there will be 365 years of available lithium in the world, however, with the increase in usage in the battery area, it is expected 50 years of lithium in the world without taking into account recycling. Lithium is 100% recyclable, meaning that it can be used again after a recycling process without the need of having to spend huge amounts of energy in extracting it from brines and then transport it. Figure 6-1 represents the supply chain of a lithium ion battery in which it has been added the step of recycling in order to improve the EROI of it.

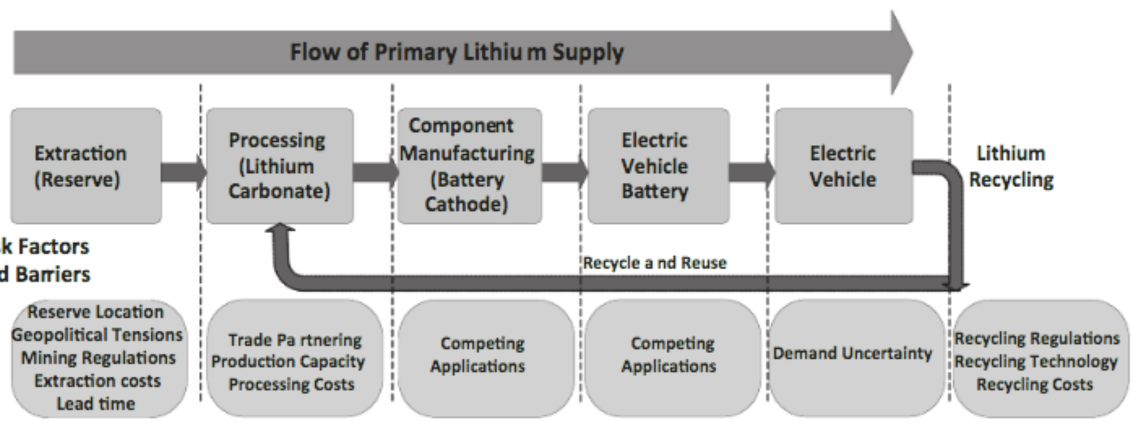


Figure 6-1. Supply chain of the recycled lithium-ion battery
Source: Hendrickson et al. (2015)

6.2 Economic Impact

One of the benefits of implementing the vehicle to grid technology is the reduction of fossil fuels both as a source of energy and vehicle fuel. This would free the oil importing economies from petroleum price spikes and shocks to the global market. Therefore, national security would be enhanced and the transfer to oil producing countries would be mitigated (Sovacool & Hirsh, 2009).

Not only the national economy would be improved but also the personal as EVs with V2G configuration owners will be able to store electricity from off-peak hours when it is cheaper and inject it when the demand increases making revenue. This action will also help to balance the electrical demand curve leading into the decrease of the electricity price (Wood, 2011).

However, despite its countless advantages, the vehicle to grid technology presents a great economical barrier. On the one hand the cost of the electric vehicles, specifically the battery that makes society to refuse this technology. Nevertheless, with the technological breakthroughs, improvements in the supply chain and economy of scale, prices are driving down but still far from conventional vehicles. On the other hand, the cost of the infrastructure, and probably the main reason why this technology is not yet a reality in our daily life. A significant investment in EVs new charging infrastructure known as smart grids is required for the use of this technology, the communication vehicle-grid in both directions has to be optimized in order to get the maximum advantage of the technology and therefore maximize generation efficiency. The grid will have to take into account millions of batteries and decide when they have to be charge and discharge in order to meet the electric demand (Gough, 2015).

6.3 Social Impact

The vehicle to grid (V2G) technology seems destined to threaten the structure of the transport business. While conventional automotive industry logic sees vehicles as merely the receivers of petroleum, the vehicle to grid strategy considers automobiles as valuable resources. Not only that, but conventional automotive logic is based in combustion, mechanical engineering and low-cost production as well as focusing on customers that prefers performance and comfort rather than a fuel economy. On the other hand, V2G strategy is centered on electrochemistry and power electronics with consumers seen as valuing fuel economy and additional revenue (Lund & Kempton, 2008).

The transition to the vehicle to grid technology would likely induce a significant loss of business for repair and maintenance companies since this modern vehicles are simpler in the way that they don't have moving parts and don't require lubricant oils, water pumps or catalytic converters among others. Consequently, oil changes, tune-ups or mandatory annual emissions, for example, won't be necessary anymore implying the loss of thousands of employments (Fontaine, 2008). However, according to Sovacool & Hirsh (2009), the most affected companies would be the ones in the petroleum industry, as they are taking advantage of the current industry infrastructure making high profits and therefore, they have an extraordinary incentive to resist and prevent a transition to vehicle to grid systems.

Last but not least, the development of the V2G technology has the goal of making available huge amounts of energy (renewable energy) as vehicles will work as distributed sources of energy, meaning that EVs could be considered as competitors to traditional forms of electricity supply. This threat has lead electric utilities to persuade network regulators to impose oppressive requirements on interconnecting and operating vehicle to grid technology (Dehaghani & Williamson, 2012).

The main problem though, and probably the major social barrier is that people and businesses are reluctant to fully embrace the opportunity of generating their own electricity in forming part of that business, it's difficult for people to accept new things and make changes in their lifestyle as everyone would rather stay in the comfort zone that they are used to. For that reason, EVs with a vehicle to grid configuration should be designed seeking the lowest alteration of lifestyles and behaviors. Following that line, according to Sovacool & Hirsh (2009), the hardware has to be designed in order that the consumer does not need to think or make any effort. In conclusion, the need of a smart connection that will take care of figure out the optimal times of charging and sell power back to the grid.

6.4 Environmental Impact

As far as environment concerns, implementing EVs with vehicle to grid technology has potential benefits. First, by reducing the amount of fossil fuels consumed and therefore the noxious emissions by promoting the purchase of electric vehicles. This new technology makes the purchase of an EV much more attractive not only because of the cheap prices of electricity but also because of the possibility of generating income by introducing the electricity back to the grid is significantly appealing to customers. Therefore, owning an EV with a V2G configuration implies the possibility of making money since it takes advantage of the electric rates, unlike internal combustion engine vehicles, which are run by gasoline that can be considered a persistent economic loss to drivers (Tsoleridis, Chatzimisios & Fouliras, 2016).

Secondly, the use of electricity that has already been generated, in other words, the injection to the grid of what would have been wasted electricity (because of the demand) that in the end has been stored in the battery acting as a source of energy. That technology in that way prevents the waste of the electricity by storing it but also prevents the generation of more electricity that could be generated in fossil fuel plants (prevents the built of new plants) by injecting the electricity stored back to the grid (Hutton & Hutton, 2011).

Third, and probably the most important is the benefit for renewable resources. The transition to vehicle to grid technology will allow renewables to be available in the market. As it has been discussed in section 3.2.2, the main drawback of renewable energy is that it is unpredictable and therefore it cannot assure a steady supply of energy that can meet the electrical demand. What's more, they also generate a significant amount of energy during off-peak hours that is wasted as the electricity generated is over the demand. Thanks to electric vehicles and its batteries, this electricity, that would be otherwise wasted, can be consumed and stored letting renewables the entrance to the electric market and raise its competitiveness against fossil fuels (Carrasco et al., 2006).

CHAPTER 7

SUMMARY, CONCLUSION AND FUTURE WORK

Chapter 7 shows a brief summary of all the areas approached in this project as well as the conclusion considering the information gathered along the project and the results obtained. This e chapter also provides a section on future work in which we suggest the next research topics that should be undertaken in order to continue and expand the scope of this project.

7.1 Summary

Energy management can be seen as important instruments for recognizing existing economic energy efficiency potentials by systematic procedures (Bertoldi & Atanasiu, 2007). Design of energy efficiency management strategies in industry, similarly, aims at both gaining knowledge and developing strategies that can assist industry with achieving energy efficiency targets. Significant energy-efficiency improvement opportunities exist in the industrial sector, many of which are cost-effective (Eichhammer & Wilhelm, 1997). Specifically in the battery industry, which is becoming a sector with significant impact on the global economy, as they have potential to provide access to renewable energy sources, energy security, reduction of GHG emissions and global warming thanks to their capacity to store energy (Rao and Rao, 2011). This projects aims to optimize lithium-ion batteries by improving their efficiency calculated by the EROI (Energy Returned on Energy Invested) value. EROI as one of the well-known methods of assessing sustainability of energy systems measures the energy efficiency of a system (Murphy & Hall, 2010). According to the literature review and the calculations developed in this study, the most efficient and sustainable way for using lithium-ion batteries for storing energy is using them as distributed sources of energy through Battery Electric Vehicles (BEVs) with a Vehicle to Grid (V2G) configuration. However, in order to reach this level of efficiency several techniques have been considered for the improvement of these batteries. Examples include expansion of the battery lifespan through optimum battery discharge or improvement of the energy management strategies along the batteries supply chain and manufacturing processes. The positive impact of the V2G configurations as a sustainable energy strategy has been well demonstrated in the literature.

7.2 Conclusion

Following the goals and objectives stated in section 1.2, the project has contributed to the literature of energy management in support of sustainable development by investigating the application of electric batteries as a sustainable energy system in management of the electric grid. Moreover, it has been understood the application of the lithium-ion batteries for electric vehicles with vehicle to grid configuration describing conditions under which batteries can perform as both storage and a source of energy, as well as evaluating social, economic and environmental impacts of using batteries as a distributed source of energy in the grid system. The project has also succeed in supporting sustainable industrial technology management by demonstrating application of strategic tools for analyzing energy efficiency in battery manufacturing focusing on both operation/supply chain and product design. The project has also studied the impact and consequences of the solutions provided in real cases through data gathered from the EVs available in the market with lithium-ion batteries and vehicle to grid configuration. Finally the project has suggested improvements for the optimization of energy use in industry according to sustainable economic development/manufacturing criteria.

Battery storage seems to be the solution to solve the energy actual situation, as it is a good target according to efficiency improvement (reduce energy consumption) as well as a good solution for injecting renewable energy to the market (reduce GHG emissions). This project concludes that the optimum way for using batteries is not only as energy storage but also as a source of energy. The benefits of using lithium-ion batteries as a distributed source of energy is that it will be eliminated the need for high-priced peak power (balance the demand curve), boost grid resiliency and increase efficiency (allowing the entrance of RE to the grid). Not only that, but also will be achieved a reduction in the source fuel and carbon emissions needed to generate the same amount of energy. Batteries are the solution for a clean, reliable and least-cost distributed energy storage for the grid.

According to the model developed in the project, in order to make batteries more efficient (increase its EROI value), there has to be a correlation between the distance traveled and the energy injected into the grid. This is due to the lifespan of the battery, in order to make batteries a sustainable source of energy there has to be a balance between the lifespan of the battery and the energy injected to the grid through the vehicle to grid technique. The more energy injected in the grid, the less cycles are available in the battery life. Therefore, the model developed in the project allows us to calculate the amount of energy that should be injected every day in the grid according to the distance traveled, or in other words, the depth of discharge that the battery has to reach in order to inject the higher amount of energy during its life.

The use of batteries as both storage and source of renewable energy has still to overcome some social and economic barriers because it has to be done a huge investment in the infrastructure (smart grid). However, it has been shown that the economic and environmental benefits that this transition would bring are countless and it is something required by the world at this time leading into a technology that has been proved more sustainable for society than solar and wind energy.

7.3 Future work

This work researches about lithium-ion batteries and its optimization by increasing their efficiency through the improvement of the EROI in EVs with V2G configuration. However, this is just a theoretical study that could be expanded in the future by designing a device able to control and optimize the energy injected to the grid from the EV vehicle according to the model presented in this project. This is taking into account the lifespan of the battery and the depth of discharge linked to the distance traveled for a specific battery capacity and range.

While in the project there is a study about the environmental, economic and social impact of implementing vehicle to grid technology, a more in depth study should consider estimating actual benefits of introducing the optimization method proposed in this this project. For example, estimating the amount of CO_2 emissions reduced (less batteries and less fuel), the amount of RE (that would have been wasted) injected in the market or the money saved by expanding the lifespan of batteries thanks to optimize the use of the battery.

Gathering data related to the battery field is difficult nowadays as companies are not likely to share their data with the market (protecting their intellectual assets by enforcing confidentiality). Therefore, more accurate data sets are needed for research, especially for estimating actual values of the energy invested in the process of manufacturing EV models. Advanced information is critical for estimating realistic EROI values.

Although analysis of the energy use has been the main focus of this project, we suggest that future work should also focus on:

Conducting research in areas concern with improving the energy returned capabilities of the batteries while expanding their lifespan Aiming to develop and test alternative methods for improving the EROI. For example focusing on the batteries and EVs operations the supply chains improvements.

Finally, the data of the model should be updated constantly as new battery models and technologies (chemistry and materials) enter the market.

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